An investigation of surgical pathways utilising femtosecond laser technology to increase the efficiency and safety of cataract surgery within a public health sector setting

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I hereby certify this is entirely my own work unless otherwise stated.

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Dedication

"Success consists of going from failure to failure without loss of enthusiasm"
Winston Churchill

This thesis is dedicated to Victoria, my wife. Her selflessness enabled me to undertake this work during a busy and demanding period of our lives.

Victoria made sacrifices and worked hard on my behalf. The thesis, therefore, is as much the result of her endurance as it is of mine.

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Abstract

The femtosecond laser (FL) has been introduced into cataract surgery within the last 10 years and continues to provoke much interest, with strong opinions on either side of the debate concerning its value; both potential and real. It offers automation and precision for several steps of cataract surgery but at a significant financial cost.

Many case series and cohort studies have been published in the academic literature, but there are only a few randomised controlled trials comparing FL assisted cataract surgery (FLACS) with the gold standard of conventional phacoemulsification cataract surgery (CPS), and these are generally underpowered. Some National Health Service (NHS) hospitals are adopting this technology but at significant financial cost and there is yet a lack of convincing evidence for any clinical benefit of this technology.

The aim of this MD(Res) project was to investigate whether FLACS technology can offer clinical benefit or with differing models of service delivery provide cost-effectiveness to public sector cataract services. The primary hypothesis was whether a FL incorporated into a ‘hub-and-spoke’ pathway (whereby one FL treats patients and feeds them into multiple operating theatres) would improve productivity, and whether these productivity gains are sufficient to offset the additional costs associated with the technology itself.

In order to address these questions this thesis comprises six studies:

1. To fully understand the running of NHS cataract theatre lists, time-motion studies (TMS) were conducted at cataract theatre lists in 5 different institutions (four NHS hospitals, one private hospital). Individual tasks, and their timings, of every member of staff were recorded. This study represents the first published TMS of cataract surgery and showed significant variability in the number of cases performed and the efficiency of patient flow between different institutions. Hypotheses were made as to factors supporting or hindering productivity, including staffing levels in individual surgical theatres and individual task allocation.

2. A hypothetical financial model was designed to compare FLACS with CPS for the provision of cataract surgery within the NHS. This study highlighted the significance of the cost of the disposable patient interfaces (PI) over the capital cost of the femtosecond laser itself. It concluded that there would need to be a significant improvement in productivity offered by FLACS over CPS, as well as significant discounting from the manufacturers of the PI, to offset the associated costs associated with this technology.

3. To evaluate the learning curve of the first 288 consecutive FLACS operations among 3 surgeons of differing grades of experience, who were naïve to the FLACS procedure. Surgical outcomes were analysed using a risk-adjusted cumulative sum method (CUSUM) to estimate the length of the learning curve for each surgeon, with regards to all complications and specifically posterior capsular rupture (PCR). The results of the pooled suggest stability in the rate of PCR after the first 16 cases.

4. A randomised controlled trial (RCT) was conducted to compare FLACS with CPS in 400 eyes of 400 consecutive patients. The analysis of the results found no statistically significant differences between the treatment arms in unaided or corrected visual acuity, refractive outcomes, phacoemulsification energy, endothelial cell loss, macular oedema, or patient reported outcome measures. The only statistically significant difference found was in the rates of posterior capsular rupture (FLACS 0%, CPS 3% p=0.03).

5. Surgeries within the RCT, described above, were performed within a high-volume surgery model. The FLACS arm was performed within a 2:1 hub and spoke model, while the CPS arm was performed with 2 theatres operating in parallel. This is the only study to date to evaluate the productivity of FLACS within a hub and spoke setting. FLACS with a hub-and-spoke model was significantly faster than CPS, with patients spending less time in theatre. This enabled a slight improvement in productivity, but not sufficient to meaningfully offset the additional costs relating to FLACS.

6. A sub-analysis of the FLACS RCT was undertaken to compare the effectiveness of manual limbal relaxing incisions (LRI) with femtosecond laser arcuate keratotomies (FS-AK) in the management of corneal astigmatism at the time of cataract surgery. All patients with corneal astigmatism greater than 0.9 dioptres (D) were offered treatment with either LRI (n=51) or FS-AK (n=53). Visual acuity, post-operative refraction, and corneal topography were recorded as well as any surgical complications. Analysis was performed according to the Alpins method. The FS-AK group had a significantly lower difference vector and higher correction index than the LRI group. 44% of patients treated with FS-AK attained a post-operative astigmatism of <0.5D compared with 20% in the LRI group.

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Chapter 1. Introduction

1.1. Background

In the current economic climate, the need to severely limit public sector spending to reduce national budget deficits has become of overriding importance. However, despite the best efforts of most societies, expenditure within the public health sector continues to increase at an unsustainable rate (Monitor, 2015b). Cataract surgery is one of the commonest and most successful surgical interventions undertaken in modern medicine (Department of Health, 2015a; Day, Donachie, et al., 2015; Allen and Vasavada, 2006). Within the National Health Service (NHS) in the UK alone, an estimated 370,000 cataract surgeries are undertaken per annum at a cost of over £300 million.(Department of Health, 2015b) There is clearly a need to limit such costs. It may be difficult in any democratic society to ration the provision of cataract surgery, but expenditure can be curtailed by improving productivity (Monitor, 2015a). This may be achieved by improving the efficiency of the cataract surgery service, by treating more patients with the same resources, and by minimising additional costs, such as those sustained from providing care and resources for complications of surgery (Qatarneh et al., 2012; Schmier et al., 2007).

Femtosecond laser (FL) technology has been recently introduced into cataract surgery in an attempt to automate and improve the efficacy of some of the surgical steps within this procedure (Nagy et al., 2009). Within the scientific literature there are numerous studies supporting its usage and continued development as more surgeons are adopting this technology and publishing their results, often in comparison with conventional phacoemulsification (CPS). However, most of its uptake, until recently, has been within the private healthcare sector because of the additional associated financial costs. To the knowledge of the author, less than ten FL systems are in service within the NHS at the time of writing. Whilst FL technology is undoubtedly initially expensive to purchase and maintain, by its very nature it offers the potential to automate some of the surgical steps. This automation has the potential, with hub and spoke delivery models, to reduce actual surgeon operating time, while maintaining and possibly improving patient safety and outcomes. Reduced surgeon operating time could lead to improved efficiency with an increase the quantity of cases undergoing cataract surgery within the same period of time. Increasing patient numbers may have the potential to offset the initial expenditure and additional costs associated with FL technology. Indeed it may have the potential to reduce overall costs if the number of patients treated can be sufficiently increased, as well as the incidence of complications are equivalent or reduced (Abell and Vote, 2014).

1.2. Epidemiology of cataracts

In 2002, the World Health Organization (WHO) calculated that there were 161 million people living with visual impairment worldwide, of which cataract accounted for 48% (Resnikoff et al., 2004). They estimated that cataract was the most common cause of blindness worldwide, affecting over 17 million people across the globe (Foster and Resnikoff, 2005). It is expected that over the next 20 years there will be an approximate doubling in the incidence of cataract and need for cataract surgery, as the world's population is estimated to increase by one third, especially in developing countries (Pascolini and Mariotti, 2012; Brian and Taylor, 2001).

Cataract surgery is the most common surgical procedure performed in the developed world (Allen and Vasavada, 2006), where the prevalence of cataract is very high among elderly people (20% with unoperated disease at age 70, rising to 50% in over 80s) (Reidy et al., 1998). In 2014-15 over 370,000 cataract operations were performed in the National Health Service (NHS) of the UK (Department of Health, 2015a), which represents an increase by a factor of 3.7 since 1989 (Black et al., 2008). The tariff paid to an NHS hospital for a routine elective day case cataract surgery is approximately £850 (Department of Health, 2015b). Based on these figures, the annual cost of cataract surgery itself within the NHS can be crudely estimated at more than £300million. It is important to note that these values do not include the costs of the pre- and post-operative clinic appointments and the management of any intra- or post-operative complications, so that the total burden of cataract disease to the NHS will be much higher. In addition, it is important to consider in any disease process, other direct healthcare costs such as the cost of hospitalization from falls associated with visual impairment (Harwood et al., 2005) and societal costs, such as lost productivity from both affected individuals and carers (Harwood et al., 2005; Sach et al., 2007).

The requirement for cataract surgery is expected to rise considerably over the next decades with increasing life expectancy, population size, patient expectations, and age-related chronic diseases associated with cataracts, such as diabetes (Minassian and Reidy, 2009). Using the rate of provision of cataract surgery from 2011 Hospital Episode Statistics data as a crude estimate of demand, average expected rates of cataract surgery are approximately 530 per 100,000 population or 3200 per 100,000 for those over 65 years old per year (Day, Wormald, et al., 2016). Historical data from the North London Eye Study estimated that 30% of people 65 years or older had visually impairing cataract in one or both eyes (Reidy et al., 1998). Ten percent of individuals in this age group in this study had already had cataract surgery. However, this is likely to be less than our current patient cohort due to the increase in the provision of cataract surgery within the NHS over the past 20 years (Keenan et al., 2007).

Improvements in technology, changing expectations of the public, greater confidence of surgeons in their ability to deliver a quality outcome and politically driven initiatives to reduce waiting times have contributed to the increase in provision of cataract surgery in the NHS (Sparrow, 2007). In the UK, thresholds for listing for surgery have generally become increasingly lenient in visual acuity terms. In 1990 less than 9% of eyes undergoing cataract surgery had an acuity 6/12 or better (Desai, 1993), while the Royal College of Ophthalmologists' (RCOphth) National Ophthalmology Database (NOD) (August 2006 – November 2010) showed that 3%, 5% and 36% of eyes undergoing cataract surgery had preoperative visual acuities of better than or equal to 6/6, 6/9 and 6/12 respectively (Day, Donachie, et al., 2015). As well as increasing the demands for cataract surgery, this lowering the visual threshold for cataract surgery also reduces the potential amount of possible visual improvement and raises the possibility of patients complaining that they are 'worse off' following surgery (Black et al., 2008).

Cataract surgery is reported to be one of the most cost-effective operations, and comparable to hip replacement surgery (Lansingh et al., 2007). Even in developed countries, which as discussed above, undertake a significant proportion of surgery for only mildly visually impairing cataract, it is estimated to be cost effective with an incremental cost per quality adjusted life year (QALY) of £13,172 over an individual's lifetime (assuming an anticipated lifespan of 10 years following surgery) (Sach et al., 2007). This is significantly below the £20k-£30k per QALY benchmark set by the National Institute for Health and Care Excellence (NICE) for a medical intervention to be cost effective.

Approximately 40% of patients eventually undergo cataract surgery on both eyes (Jaycock et al., 2009; Day, Donachie, et al., 2015). A recent systematic review funded by the National Institute for Health Research (NIHR) concluded that second eye cataract surgery was associated with a clinically meaningful improvement in depth perception, binocular visual acuity was slightly improved but perhaps of limited clinical value, there was no significant improvement in self-reported visual function or health related quality of life (Frampton et al., 2014). Second eye cataract surgery is thought to be less cost-effective than first eye surgery, but still worthwhile and cost-effective, as the systematic review estimated the probability of cost effectiveness at willingness-to-pay thresholds of £10,000 and £20,000 to be 100% (and therefore within the threshold set by NICE). A Swedish National Cataract Register study demonstrated better self-assessed visual outcomes and satisfaction after second eye cataract surgery in comparison to a comparable group of unilateral surgery only patients(Lundstrom et al., 2001). A national study in the U.S. found that a group of 243 patients having second eye surgery within 12 months, demonstrated a 61% increase in VF-14 score(Javitt et al., 1995). Despite this, second eye cataract surgery has been one of several areas where clinical commissioning groups have recently tried to ration surgery to cut costs. A report by RCOphth highlights the impact that recent efficiency savings expected from the NHS has had on cataract surgery (The Royal College of OphthalmologistsThe Royal National Institute of the Blind, 2011). A recent report by Monitor, the Government's regulator for healthcare in England, states, "*Elective care services across England are generally under pressure to do more with less. Their costs are increasing and demand is growing. Similar pressures affect all NHS care: they are the source of the £30 billion gap between NHS funding and the projected costs of care in 2021 that the NHS Five Year Forward View highlights and new care models seek to address. For these* *reasons, improving productivity in elective care is critical for NHS providers…. Improving productivity does not mean simple cost cutting: it means increasing the efficiency of elective care while at the same time improving or maintaining its quality*."(Monitor, 2015a).

1.3. History of cataract management

Mark 8:22-25-*"And He cometh to Bethsaida; and they brought a blind man unto Him, and besought Him to touch him. And He took the blind man by the hand, and led him out of the town; and when He had spit on his eyes, and put His hands upon him, He asked him if he saw ought. And he looked up, and said, "I see men as trees, walking." After that He put His hands again upon his eyes, and made his look up: and he was restored, and saw every man clearly"*

1.3.1. Couching to extracapsular cataract surgery

The oldest documented case of cataract was in a statue from the 5th dynasty of Ancient Egypt. The cataract is represented by a statue of a male priest with a white pupillary reflex in one eye (Ascaso and Cristóbal, 2001). The most plausible hypothesis for the first cataract treatment was in Ancient Egypt based on a mural (c. 1200 BC) demonstrating an oculist treating the eye of a workman, using a long instrument, by couching the cataract into the vitreous cavity (Ascaso et al., 2009). However the first description of the couching technique was in an Indian medical treatise dating around 800 BC (Duke-Elder1969, n.d.). The text describes using a curved needle to push the lens into the rear of the eye, out of the visual axis. The eye would later be soaked in warm clarified butter and then bandaged. This method was described as successful but with caution that it should only be performed when absolutely necessary!

The longevity of couching of thousands of years far eclipses any of the newer methods for treating cataracts, as it was the procedure of choice until the first documented cataract extraction was performed in 1748 in France by Jacques Daviel (Dolezalová, 2005). Indeed it is still used in some parts of Africa (Savage-Smith, 2000). Daviel was the oculist to King Louis XV. His extracapsular technique marked the beginning of the modern era in cataract surgery (Dolezalová, 2005). Interestingly, the advent of a rival technique to couching divided opinions with vocal proponents on each side. During this phase, two famous composers Johann Sebastian Bach and George Frideric Handel both elected to undergo couching by the same surgeon, John Taylor (1703-1772); unfortunately both went blind (Zegers, 2005). Albrech von Graefe (1828-1870) refined the technique of extracapsular cataract surgery, with his eponymous knife and 'modified linear extraction'.

1.3.2. Intraocular lenses

The era of intraocular lenses began with Sir Harold Ridley (1906-2001) who worked at both Moorfields Eye Hospital and St Thomas' Hospital. His interest in developing an artificial lens was allegedly catalysed by a medical student, who, while watching a cataract operation questioned why the lens was not replaced. He was inspired to choose polymethylmethacrylate (PMMA) as the material for the IOL as he had observed that it was an inert material in the eyes of Royal Air Force pilots in World War II who had sustained intraocular foreign bodies from shards of their PMMA cockpit canopy (Ridley, 1952). On 29th November 1949, Ridley implanted the first IOL at St Thomas' Hospital. The first IOL was manufactured by Rayner company of Brighton & Hove (Spalton, 2009), yet it was many decades until IOL implantation became commonplace. It was in 1981 that the US Food and Drug Administration approved Peter Choyce's Choyce Mark IX IOL as the first IOL to be approved in the United States. Today, approximately 14 million IOLs per annum are implanted worldwide.

1.3.3. Phacoemulsification

In a 1994 paper, Charles D Kelman recalls how he was inspired to reduce the size of the incision needed for cataract surgery to improve post-surgical rehabilitation and the amount of surgically induced astigmatism (Kelman, 1994). In the 1960s, Kelman was awarded a grant to explore his hypotheses. He first searched for a chemical which would dissolve the crystalline lens, however there were none which did not also destroy the corneal endothelium. After spending most of the research funds on various surgical instruments including drills and vibrators, Kelman concluded that the movement of the lens and the denuding of the endothelium were the two greatest challenges to overcome. Kelman hypothesized that only a rapidly accelerating instrument could move through lens matter without pushing it away, and was subsequently inspired while in the dentist's chair by the ultrasonic probe. After years of experiments on animals, the first human phacoemulsification operation was performed on an already blind eye scheduled for enucleation; the operation lasted 76 minutes (Kelman, 1967). It was not until many years later that phacoemulsification became mainstream. Refinements which enabled phacoemulsification to become the technique used for 99.7% of cataract operations in the UK in 2001-2006 included improvements in the phacoemulsification machine (including smaller handpieces and better fluidics), the advent of foldable IOLs (allowing smaller incisions), the invention of the continuous curvilinear capsulorrhexis (CCC) (allowing more reliable implantation of the IOL in the bag), and the development of viscoelastic substances (to facilitate the operation and protect the endothelium) (Jaycock et al., 2009).

1.3.4. An Overview of Modern Phacoemulsification

There are variations on surgical technique, but the fundamental steps of conventional cataract surgery are as follows. The patient receives pre-operative

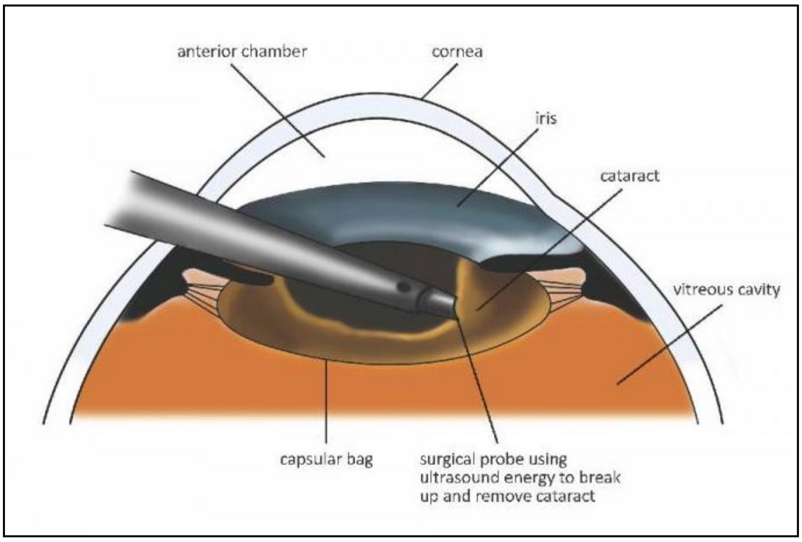


Figure 1.3.4-A Anatomy of a phacoemulsification operation

dilating drops to widen the pupillary aperture to allow access to the cataract and topical iodine onto the conjunctiva and eyelashes for infection prophylaxis. The operation is conducted in an operating theatre under sterile conditions. The operation is generally performed under local anaesthesia, with general anaesthesia accounting for less than 5% of cases in the UK (Jaycock et al., 2009). A sterile drape is placed over the patient's face, a slit is made in the drape to allow access to the eye and a speculum is inserted to open the eyelids.

One main incision, usually no more than 3mm wide, is made in clear corneal tissue, at the limbus or within the sclera, accompanied by one or two smaller adjacent incisions to allow a second instrument into the anterior chamber. A circular opening is made in the anterior lens capsule, the continuous curvilinear capsulorhexis (CCC). This is generally done with forceps or a needle. The cataract is then separated from its capsule by an injection of saline solution between the anterior lens capsule and the lens substrate. This injection, known as hydro-dissection, circulates around the lens and breaks any adhesions allowing the cataract to be rotated freely within its capsule. The phacoemulsification probe can then be inserted through the main incision (Figure 1.3.4-A). Controlled by a multi-axial foot-pedal, this probe allows irrigation of fluid into the anterior chamber to maintain the intraocular pressure. A second aperture on the instrument allows vacuum aspiration from inside the eye. Finally, the tip of the probe is able to oscillate at ultrasonic frequencies (40,000 times a second). The energy delivered by this vibration emulsifies the hard nuclear lens matter. Often with the assistance of a second instrument to manipulate the cataract, the lens is broken into several smaller pieces, which can then be aspirated from the eye by the phacoemulsification probe. Once the cataract has been removed from the eye, the phacoemulsification probe is withdrawn, and an irrigation-aspiration probe can be inserted into the anterior chamber. The functions of this probe are the same, with the exception of the high frequency vibration. This probe allows the surgeon to remove the softer peripheral remnants of the lens epithelium (the cortex) from inside the capsular bag with minimal risk of trauma to the capsule. Once the last remnants of the cataract have been removed, the intraocular lens can be inserted into the eye. Modern materials allow IOLs to be folded and inserted via forceps or an injector through the original wound. The IOL is generally placed into the capsular bag, unless it has been damaged during the course of the operation, which occurs with an expected frequency of about 2% (Day, Donachie, et al., 2015). This is the most common significant intraoperative complication and is known as posterior capsule rupture (PCR) or tear. The small size of the corneoscleral wound means that it is generally watertight under physiological conditions and does not require a suture, although the wound can be sutured if there are doubts as to its competency. Finally, an antibiotic is injected into the anterior chamber to reduce the risk of post-operative endophthalmitis (ESCRS Endophthalmitis Study Group, 2007).

Postoperatively, most surgeons treat their patients with prophylactic topical antibiotics and anti-inflammatory agents, such as corticosteroids, either in separate formulations or in combination (The Royal College of Ophthamologists, 2010). Patients apply the drops several times a day for several weeks, depending on the postoperative course.

1.4. Overview of Use of Femtosecond Lasers in Cataract Surgery

1.4.1. Device Description

Applying laser energy within transparent tissues requires high irradiances, and a tightly focussed and short-pulsed spot size. This mechanism, called dielectric breakdown, allows for a highly localised delivery of laser energy within a transparent tissue, such as the cornea. The absorption of the photon energy ionises the tissue, producing plasma with a temperature between 100-300°C, which in turn, vapourises the tissue at the focus of the laser. This process is known as photodisruption. Rapidly expanding and contracting bubbles of tissue vapour can rupture adjacent tissue. When applied to the cornea as a series of adjacent laser spots, these bubbles cleave planes between adjacent collagen fibrils (T. V. Roberts et al., 2012).

The femtosecond laser can be focused precisely at a given depth within the cornea or crystalline lens as the infrared wavelengths (1053 nanometres (nm)) emitted are not absorbed by the tissues of the cornea or anterior lens capsule (Schumacher et al., 2008). Due to the ultrashort pulse (10^{-15} seconds), the laser can create multiple gas bubbles side by side, with minimal collateral tissue damage. This effectively allows the laser to cut through tissue with micrometre accuracy. The laser energy delivery and subsequent micro-cavitation bubble creation, can be linked to real-time anterior segment optical coherence tomography (OCT) or Scheimpflug imaging to accurately and safely perform pre-planned cuts within the anterior segment, without damage to important ocular structures such as the corneal endothelium and posterior lens capsule.

1.4.2. Femtosecond laser assisted cataract surgery (FLACS)

Currently, there are five femtosecond laser platforms which are approved for use in cataract surgery: Catalys (Abbott Medical Optics, Santa Ana, California), Femto LDV Z8 (Ziemer Ophthalmic Systems AG, Switzerland), LensAR (LensAR, Orlando, Florida), the LenSx (Alcon Laboratories, Inc., Fort Worth, Texas) (Figure 1.4.2-A), and VICTUS (Bausch & Lomb, Rochester, New York). As of January 2015, over 400,000 cataract procedures have been performed with the LenSx laser in 67 countries with over 780 laser machines (Data from Alcon).

All femtosecond lasers provide the laser operator with an image of the target tissue. The LenSx device (Figure 1.4.2-A) is directed by means of an integrated video microscope for a real-time ‘en-face’ view of the tissues and an OCT scanner which allows cross-sectional views through the cornea and lens. A disposable applanating contact lens and suction ring are used to dock the subject’s eye to the laser via an arm which extends from the body of the machine and can be controlled by a joystick. A vacuum is applied to the tear film to fixate and applanate the globe to the patient interface allowing for the precise placements of the laser spots. While the applanating contact lens is docked onto the eye, there is usually an accompanying rise in the intraocular pressure within the anterior chamber (Ebner et al., 2017).

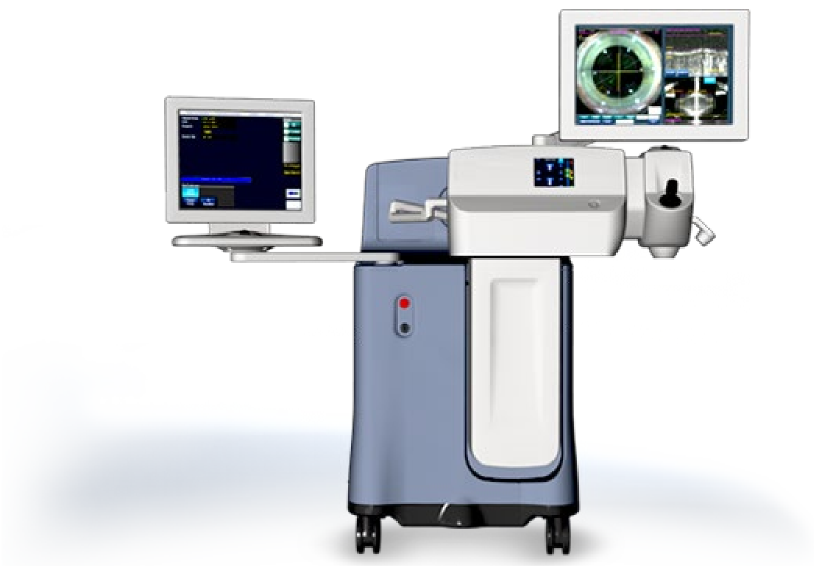


Figure 1.4.2-A The LenSx Femtosecond laser (Alcon Inc.)

The femtosecond laser can be used to precisely automate 4 stages of the cataract operation. At the level of the cornea, the laser can create the main incisions and side ports needed for access to the anterior chamber. In addition, by making arcuate cuts within the corneal stroma at its periphery, the laser can effect changes in the curvature of the corneal to change the cylindrical component of the cornea's refractive power, allowing the surgeon to reduce corneal astigmatism. The FL can also be used to mark the cornea at its steep axis for the subsequent alignment of a toric IOL (Dick and Schultz, 2016). At the level of the crystalline lens, the laser can create a precise circular opening on the anterior capsule, the capsulotomy. Finally, the laser can be used to assist in the fragmentation or softening of the lens by cutting the lens into sections or even a grid pattern. Real time OCT imaging of the anterior segment allows for the automated planning of safe zones, to avoid laser application from a pre-determined distance from the pupillary margin or posterior capsule.

Following the application of the laser energy to the tissues, the vacuum is release and the patient is 'undocked' from the machine. The surgeon can then commence the manual portion of the intraocular surgery. If the laser was used to create the clear corneal incisions (CCI) the surgeon will usually need to open these wounds with a blunt spatula. Once a viscoelastic device has been injected into the anterior chamber, the next task is to remove the disc of anterior capsule which has been cut away from the capsulotomy rim. Hydrodissection and hydrodelineation are facilitated by the presence of intra-lenticular gas bubbles formed by the laser. Balloting the cataract will induce a partial pneumodissection as the gas bubbles escape anteriorly and less fluid is required to complete the dissection/delineation. The phacoemulsification probe can then be used to remove the remaining lens matter with a combination of phacoemulsification and aspiration, this stage having been facilitated by the lens segmentation pattern. The removal of cortical strands is often more challenging than CPS because of the increased adherence of the cortex to the capsule and the lack of freely floating filaments. From this stage onwards, the operation is in the main completed as described for conventional phacoemulsification.

1.4.3. Published Clinical Experience with FLACS

1.4.3.1. Clear Corneal Incisions

The clear corneal (micro-) incision (CCI), used by most cataract surgeons to gain access to the anterior chamber during cataract surgery is one aspect which the femtosecond laser can automate. The length and shape of the incisions are important factors in corneal wound stability. A cadaveric study demonstrated greater architectural stability and reproducibility with FL CCIs compared to CCI wounds made manually with a disposable keratome (Masket et al., 2010). In vivo, a study performing corneal wave-front analysis on groups of CPS and FLACS patients showed that the CCIs created with a keratome knife induced greater high order aberrations at one month post operatively compared to the laser incisions (Serrao et al., 2017; Serrao, Lombardo, Schiano-Lomoriello, et al., 2014). There also appears to be a lower incidence of ragged Descemet’s membrane (DM) morphology at the inner aspect of the wound and DM tear/detachment in FL-created CCIs compared with those created manually with keratomes (Titiyal et al., 2017). It has also been postulated that a FL CCI may result in less endothelial cell loss (ECL) at the wound site than a manual CCI with less of an increase in local corneal thickness at one month (L. Mastropasqua, Toto, A. Mastropasqua, et al., 2014). However, occasionally the FL CCI may be incompletely formed which results in difficulty entering the anterior chamber (T. V. Roberts et al., 2013). An in vitro study of 16 human corneo-scleral buttons found that FL CCIs in human corneas showed no differences in stromal inflammatory cell response but a significantly higher cell death rate than manually performed incisions, indicating an upregulated postoperative wound-healing response (Mayer, Klaproth, Hengerer, Kook, et al., 2014). Another cadaveric study including 90 human corneas demonstrated increased interleukin-18 positive cells in the adjacent stroma of FL-CCIs compared to manually created wounds, but no increase in interferon gamma, when low energy spot settings were used (Toto et al., 2016).

The femtosecond laser does allow for the creation of custom CCI profiles, with more customisation than is practically possible with a manual keratome. Using a Catalys platform, tri-planar CCIs created with a reverse angle for the first plane (Figure 1.4.3-A) withstood greater IOPs before leaking peri-operatively and had lower incidence of day 1 post op wound leakage on applying pressure (Seidel positivity) than traditionally constructed tri-planar femtosecond or manually created tri-planar CCIs (Donnenfeld et al., 2018). There were no significant differences in mean IOP before leakage between the conventional CCIs whether constructed by laser or keratome. However, the inherent differences between a FL which creates an incision plane by ablating corneal tissue and a manual keratome which cleaves through tissue are borne out in a study examining wound architecture using optical coherence tomography (OCT) demonstrating FL CCIs had a higher incidence of posterior wound retraction at one and three months (X. Wang et al., 2018).

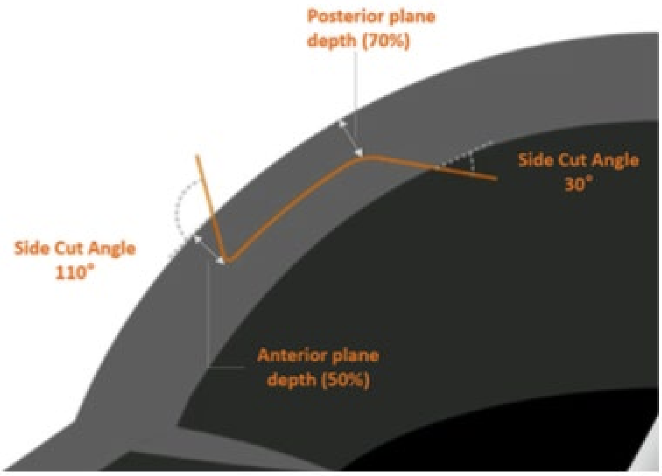


Figure 1.4.3-A Architecture of a femtosecond triplanar CCI with a reverse side cut of 110 degrees (From Donnenfeld et al. JCRS. 2018)

1.4.3.2. Arcuate/Astigmatic Keratotomies

Corneal astigmatism in patients undergoing cataract surgery is common. In one study approximately 40% of patients were reported as having more than 1 dioptre (D) and 10% more than 2D of corneal astigmatism (Khan and Muhtaseb, 2011). Similarly, in other studies, corneal astigmatism between 0.25D and 1.25D was observed in 64.4% and in 22.2% was greater than 1.50D (Ferrer-Blasco and Montés-Micó, 2009). Therefore, failing to address corneal astigmatism at the time of cataract surgery can clearly result in unaided distance visual acuity (UDVA) significantly less than the visual potential. This has been shown to be associated with reduced quality of life (Tahhan et al., 2013; Nejima et al., 2015).

To reduce post-operative spectacle dependence and maximize unaided distance visual acuity UDVA, various techniques have been introduced to reduce corneal astigmatism at the time of cataract surgery. These include on-axis incisions with or without opposite clear corneal incisions, limbal relaxing incisions (LRIs), femtosecond laser assisted arcuate keratotomies (FS-AK), toric IOLs, and post cataract surgery excimer laser refractive surgery (bioptics) (Titiyal et al., 2014; Javier Mendicute et al., 2009; Qammar and Mullaney, 2005; Abbey et al., 2009; T. C. Y. Chan et al., 2015).

The main drawbacks of LRIs are the lack of reproducibility of incision length and depth leading to often unpredictable results (Lim et al., 2014; Kaufmann et al., 2005). There may also be a degree of increased post-operative discomfort and although complications are rare, infection within the LRI, corneal melt and perforation have been described.

Femtosecond laser-arcuate keratotomy (FS-AK) can relax and effectively flatten the steepest meridian of corneal astigmatism by precisely incising the corneal stroma. Indeed, it is possible to create intra-stromal FS-AKs which avoid incising the epithelium, negating additional post-operative ocular surface symptoms and risks of infection.(Day, N. M. Lau, et al., 2016; Day and Stevens, 2016a) When FLACS is being performed, the inclusion of FS-AKs can be accomplished in a matter of only a few additional seconds as the laser performs its other functions. Due to the automated nature of the technique, the incisions are precise and reproducible with several studies showing a benefit in post-operative corneal astigmatism and unaided visual acuity (T. C. Y. Chan et al., 2015; Nejima et al., 2015; Rückl et al., 2013; Day, N. M. Lau, et al., 2016). However, the management of large amounts of corneal astigmatism, greater than 1.5D, may still require the use of a toric intraocular lens due to the inherent limitations of astigmatic keratotomy techniques.

1.4.3.3. Anterior Capsulotomy

Potential benefits of laser-delivered capsulotomy instead of manually created CCC include a more centred and more circular opening, which in turn may allow better IOL centration (L. Mastropasqua, Toto, Mattei, et al., 2014; Nagy et al., 2011). Several studies have demonstrated less IOL decentration after FLACS compared with manually created CCC (Kránitz et al., 2011; Nagy et al., 2011; Kránitz et al., 2012). This is promoted as one of the main benefits of FLACS, especially for patients where lens position is of increased importance, such as when multi-focal IOLs are used. However, this is perhaps a contentious benefit. In a prospective case study series of 255 eyes undergoing manual CCC, there was no difference in IOL tilt or decentration between well centred or eccentric CCCs (Findl et al., 2017). In addition, a case-control study which investigated the use of premium IOLs in patients undergoing CPS and FLACS showed no significant difference in mean postoperative spherical equivalent refractive error or mean absolute refractive prediction error, although higher order aberrations were not investigated (Lawless et al., 2012). Similarly, a randomised intra-individual comparison of 50 patients receiving FLACS and CPS to each eye showed no differences in terms of visual acuity, central corneal thickness, macular thickness, or lens decentration at 1 week and months 1, 3 and 6 (Mursch-Edlmayr et al., 2017). Interestingly, a one year follow up study of 33 patients undergoing FLACS in one eye and CPS in the other eye showed less deviation in the size of the anterior capsulotomy in the FLACS group, but this did not translate to a difference in corrected distance visual acuity (CDVA), ELP or refractive error (Panthier et al., 2017).

A major concern of FL capsulotomy creation are reports of an increased risk of anterior capsular tears compared with manual CCC. Anterior capsular tears may occur in relation to, or independent of, incomplete capsulotomies or where focal tags exist. A dimple down technique has been described in the management of focal tags (Arbisser et al., 2013). In a study of over 4000 eyes in a single centre, an incidence of anterior capsular tears of 1.84% with FLACS versus 0.22% in manual CCC was reported (Abell et al., 2015). Other studies have shown conflicting results, with a case series of 1,000 FLACS (using the same device as the study described above) having an anterior capsular tear rate of only 0.1% (Day et al., 2014). A number of hypotheses have been proposed to account for the increased rate of capsular tears associated with FLACS, including patient movement during capsulotomy formation and irregularities at the capsulotomy edge. Studies have aimed to evaluate the capsulotomy edge using scanning electron microscopy (SEM). A SEM study comparing the removed anterior capsule of 12 manual CCCs with 48 FL capsulotomies of varying energy settings demonstrated increasing irregularity of the capsulotomy edge (Figure 1.4.3-A) with increasing FL energy settings (L. Mastropasqua et al., 2013). The irregularity seems to be independent of which FL device is used (Harthi MD et al., 2014). Another SEM study examined the capsulotomy edges compared with manual CCC edges using objective metrics such as arithmetic mean deviation of the surface and found increased irregularities in the FLACS groups (Serrao, Lombardo, Desiderio, et al., 2014). A SEM and atomic force microscopy evaluation of FL capsulotomies and manual CCCs modelled that the smooth edge of CCCs result in the uniform distribution of forces compared with focal high stress concentrations in frayed or notched portions of FL capsulotomies (Lua et al., 2016). However, this has not been fully borne out in mechanical testing (Auffarth et al., 2013; Sándor et al., 2014). Indeed, a prospective inter-eye comparison tested the breaking force and breaking strain of capsulotomy samples of 39 patients with bilateral cataracts having CPS in one eye and FLACS in the other and found no differences in the mean breaking force or breaking strain between the CPS and FLACS group (T. Chan MBBS et al., 2017). It appears that there is a degree of irregularity in the FL capsulotomy edges compared to manual CCC, the precise nature of which varies with the laser platform and settings used but is present in all currently used devices,. This irregularity may be responsible for some degree of weakness of FL created CCCs and surgeons should be minded about this possibility in FLACS and adapt their technique accordingly.

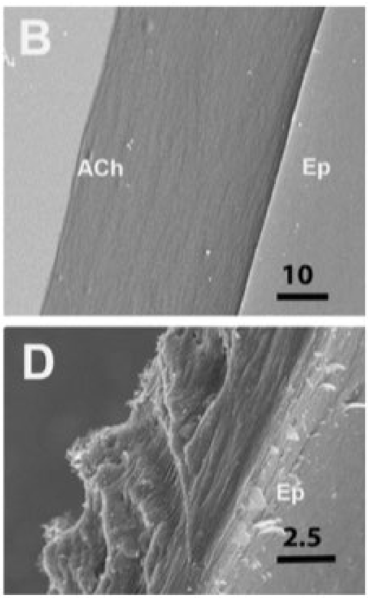


Figure 1.4.3-A Scanning electron microscopy images of (B) manual CCC and (D) FL capsulotomy edge. From Lua, M. R., Oertle, P., Camenzind, L., Goz, A., Meyer, C. H., Konieczka, K., et al. IOVS (2016).

It is important to note, that the femtosecond laser is not the only device available for creating automated CCCs. Indeed, the advent of the FL in cataract surgery has appeared to generate interest in exploring alternative, single-use, disposable, and portable technologies for CCC in order to automate this step within cataract surgery whilst obviating the substantial capital outlay costs for a FL device. In late 2015, the Zepto device (Mynosys Cellular Devices, Inc.) was given Conformité Européene (CE) approval. This device consists of a disposable handpiece with an elastic circular nitinol element at its tip, encased in a soft silicone suction cup (D. F. Chang et al., 2016). The tip is inserted into the anterior chamber through a 2.2mm corneal incision. Once inside, the silicone cup is placed centrally and suction is applied to oppose the capsulotomy ring to the capsule. Brief pulses of electricity are discharged through the nitinol ring to create the capsulotomy, after which the suction cup is released. The disposable handpiece is connected to an external control console operated by an assistant for applying suction, energy, and releasing. However in the largest case series of 100 consecutive patients treated with this device there was a reported 28% incomplete capsulotomy rate (focal tags 18%, broad attachments 10%) (Hooshmand et al., 2018).

Similarly, the Capsulaser (Capsulaser) is a microscope-mountable device featuring a laser focused on a trypan blue–stained anterior capsule delivering a singular circular pattern to create a CCC. The Capsulaser's application to the capsule is continuous, unlike the femtosecond laser's postage stamp perforations. It is understood that the irradiation causes the conversion of type IV collagen to amorphous collagen at the edge of the capsulotomy which may offer more elasticity and tear strength. As yet no peer reviewed studies exist for this device, although initial reports are encouraging (personal correspondence, Richard Packard).

Another potential benefit of a more circular capsulotomy and a more centred intraocular lens is a more consistent overlap between the edge of the capsulotomy and the edge of the IOL (Nagy et al., 2011; Kránitz et al., 2011). Better overlap between the lens edge and the capsulotomy may reduce the incidence of posterior capsular opacification (PCO) post operatively (Kovacs et al., 2014).

PCO is one of the most common post-operative complications after cataract surgery. Theoretically, by creating a better overlap of the capsulotomy edge and IOL optic, FLACS could reduce need for subsequent posterior capsulotomy by reducing migration of lens epithelial cells (when used in conjunction with a square-edged optic design) (Findl et al., 2010). Although Nd:YAG capsulotomies are a relatively low cost, low risk procedure, it does require additional visits of the patient to their ophthalmology service, which leads to patient and societal costs. A retrospective study of 39 CPS and 40 FLACS eyes showed an increased PCO level on digital retro-illumination photographs of the posterior capsule in the CPS group between 18 – 26 months after surgery (Kovacs et al., 2014). A retrospective cohort study of 1534 eyes showed FLACS Nd:YAG capsulotomy rate of 11.6% compared with 15.2% in CPS over 3 years (p=0.04) (Tran et al., 2016).

1.4.3.4. FL-assisted Nuclear fragmentation

In vitro and animal studies have demonstrated that phacoemulsification energy causes oxidative stress and free radical production which lead to cellular injury to the corneal endothelium.(Murano et al., 2008; Shin et al., 2009) Adopting techniques to reduce the effective phacoemulsification time (EPT) is considered good practice among cataract surgeons to limit such effects. FLACS has been designed to pre-treat the lens, using linear or fragmentation patterns to segment the nucleus or soften harder cataracts with the intention of reducing thermal or ultrasound energy delivered to the corneal endothelium (Conrad-Hengerer, Hengerer, Schultz, and Dick, 2012a; 2012b). Different patterns of laser grids applied to the lens nucleus may influence the amount of ultrasound energy delivered to the cataract (Conrad-Hengerer, Hengerer, Schultz, and Dick, 2012b; Ahn et al., 2016). EPT correlated with density of lens opacity (LO) in 150 eyes undergoing cataract surgery but was significantly reduced in the FLACS group of 88 eyes for all grades of LO compared with CPS (Mayer, Klaproth, Hengerer, and Kohnen, 2014). In another series of 124 eyes the positive correlation between Scheimpflug densitometry of the lens and cumulative dissipated energy (CDE) in FLACS was confirmed (Al-Khateeb et al., 2017).

In a case-control study, the amount of phacoemulsification energy delivered intraocularly to cataracts pre-treated with femtosecond laser was reduced by an average of 84%, with 30% of patients not requiring any phacoemulsification energy whatsoever to remove the cataract (Abell, Kerr, and Vote, 2013b). In a randomised controlled study (RCT), Palanker et al found that phacoemulsification energy was reduced by 39% in eyes treated with FLACS compared with PES (Palanker et al., 2010). Interestingly, in a RCT of 400 patients (200 CPS, 200 FLACS) treated with an active fluidics phacoemulsification machine, there was a reduction in CDE in the FLACS group but this did not translate into a difference in ECL (Hida et al., 2017).

Reduced phacoemulsification energy may translate into reduced ECL, which reduces the risk of post-operative corneal decompensation and bullous keratopathy. Several studies have shown reduced ECL after FLACS compared with CPS (Conrad-Hengerer et al., 2013; Krarup et al., 2014; Abell, Kerr, et al., 2014). One intra-individual study showed no difference between FLACS and CPS in ECL at 3 months (Krarup et al., 2014). There are many difficulties in trying to conclusively demonstrate whether FLACS is less traumatic for the endothelium compared to CPS. Pseudophakic bullous keratopathy (PBK) is sufficiently rare that a prospective RCT to investigate for this would require a vast number of operations to be sufficiently powered and need to correct for many confounding variables. A 2016 Cochrane review found no difference in ECL in 1638 cases (Day, Gore, et al., 2016). A 2016 Canadian meta-analysis of 14,567 eyes showed a difference of 55cells/mm^2 in favour of FLACS but whether this is of clinical significance is debatable. Perhaps the best way to tease out an effect is to examine the effects of FLACS on the endothelium of high risk groups, namely mature cataracts or patients with endothelial compromise. A prospective nonrandomised cohort study comparing FLACS with CPS in grade 4-5 hard nuclei demonstrated reduced EPT, and reduced ECL in the FLACS group (11.4% ± 12.1 in FLACS, 25.7% ± 18.9 in CPS at one month, $p<0.001$) (Xinyi Chen MD et al., 2017). However, a single-centre retrospective series of 207 eyes (FLACS n=64, CPS n= 143) with Fuch's endothelial dystrophy did not show a statistically significant differences in rates of corneal decompensation (FLACS 17%, CPS 10%, p=0.18) (Zhu et al., 2018).

1.4.3.5. Use of FLACS in complicated cataract surgery

The speed of capsulotomy formation by the FL is dependent on the specific platform, but commonly occurs in less than 3 seconds. This can facilitate opening the capsule of intumescent white cataracts reducing the risk of complications of posterior extension (Conrad-Hengerer, Hengerer, Joachim, et al., 2014; Titiyal et al., 2016). Case reports of FL capsulotomy completion in other anterior capsular anomalies, such as Alport's syndrome, have been published (Barnes and Roth, 2017). A technique for rescuing an emigrating CCC using a FL has been described (Dick and Schultz, 2014a). Postoperatively, there have been several case reports published on its use in anterior capsule contraction/phimosis (Schweitzer et al., 2015; Gerten et al., 2016; Ibarz et al., 2017). A small case series demonstrated the safety of FLACS in patients with previous radial keratotomies, including successful anterior capsulotomies with no capsular tags (Noristani et al., 2016).

The FL has been showed to be a useful and safe adjunct in a series of 47 eyes subluxed cataracts selected for FLACS where manual CCC can be especially problematic due to lack of lens support to allow countertraction, with over 90% of capsular bags successfully retained (Chee et al., 2017).

The FL has been used to transect IOLs which require exchange (Anisimova et al., 2017) and can be used without adverse effect in cataract surgery with coexisting phakic IOLs and low endothelial counts before phakic IOL removal (Lee et al., 2017). The FL can also be used to perform a primary laser posterior capsulotomy just prior to or just after IOL insertion (Haeussler-Sinangin et al., 2016; Schojai et al., 2017). It has also been used to this effect in paediatric congenital cataract cases (Bordin and Vizzari, 2016).

1.4.3.6. Complications of FLACS

The risks of anterior capsular tear are discussed above. Fortunately for all stakeholders, the rates of complications of cataract surgery are low. Therefore, large studies are required to be adequately powered to investigate differences in safety between FLACS and CPS. One meta-analysis of RCTs and cohort studies of 14,567 eyes found an increased rate of posterior capsular rupture (PCR) in FLACS (RR, 3.73; 95% CI, 1.50-9.25; $p<0.005$) (Popovic et al., 2016). The largest

RCT to investigate complication rates with FLACS compared to CPS published to date included 200 eyes and reported one anterior capsular tear in the FLACS group and no events of PCR in either group (Conrad-Hengerer et al., 2015). Within the published RCTs the rates of PCR are cumulatively lower than expected (overall rate 1/976, 0.1%). This perhaps reflects patient selection for FLACS studies and/or the senior expertise of the surgeons undertaking them. In many such published studies, included patients are often within the private sector and self-paying, further increasing bias and limiting relevance of these studies in public health sector cataract surgery. With such low rates of complications, many studies are simply underpowered to detect differences in safety, requiring many thousands of cases to detect such differences. A retrospective review of 3371 FLACS and 3784 CPS in the public sector in the US found increased risk of vitreous loss in the CPS group compared to FLACS (1.4% vs 0.8%, $p<0.05$) (Scott et al., 2016), while Abell et al.'s case-control study of over 4000 surgeries did not find a difference in the rate of PCR (0.43% vs 0.18%, N.S.)(Abell et al., 2015). The EUREQUO case control study compared 2814 FLACS cases with 4987 CPS and found no significant difference in the PCR rates of 0.4% and 0.7% ($p=0.79$) respectively (Manning et al., 2016).

A single case report describes a limited supra-choroidal haemorrhage in a myopic patient (AL 27.57mm) after multiple failed docking attempts (Bozkurt and Miller, 2016).

1.4.3.7. Future applications of FLACS under current investigation

A consistently sized and very reproducible sized capsulotomy allows for the design of intraocular lenses which are secured within the plane of the CCC, with haptics either side of the anterior capsular edge (Figure 1.4.3-A) (Thompson, 2018). Theoretical benefits of such IOLs could include better refractive outcomes from a more consistent effective lens position (ELP) and less long-term decentration or subluxation, yet these perceived benefits have yet to be borne out in longer term, comparative studies.

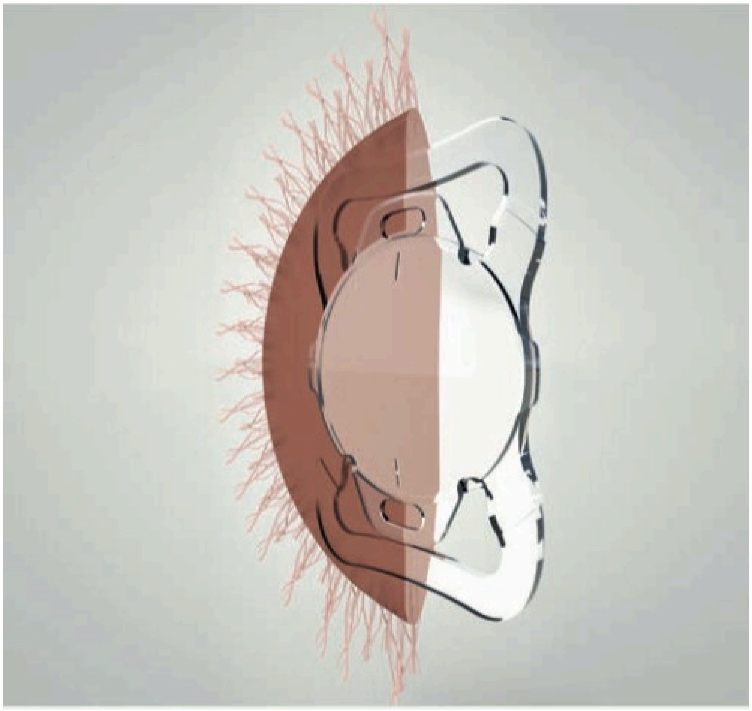


Figure 1.4.3-A The FEMTIS IOL (Oculentis) which features a plate haptic design for intracapsular fixation and four smaller haptics which are enclavated in front of the capsulotomy. Figure from Next Frontier in IOL Designs, Supplement to Cataract & Refractive Surgery Today Europe, October 2017.

A laboratory study has demonstrated the use of a femtosecond lens to change the refractive properties of an intraocular lens ex vivo (Nguyen et al., 2018). The femtosecond laser device used in this study operated at an energy level below the threshold for ablation or cutting. It appears to induces chemical changes in the IOL substrate which affect its refractive index, without affecting the overall modulation transfer function of the IOL and is biocompatible in a rabbit model (Bille et al., 2017; Sahler et al., 2016; Werner et al., 2017). This application of FL technology has yet to be performed in vivo on a human, but may allow refining the post-operative refraction including toricity or multifocality.

As discussed above, FLs have been used to perform a primary posterior capsulotomy at the end of FLACS (Schojai et al., 2017; Dick and Schultz, 2014b). Advantages of this technique would include definitively superseding the previous attempts to limit PCO in the visual axis by changing IOL material or design. This study reported this technique to be safe with no increased rates of CSMO or other complications. However, the requirement to redock the globe with the FL at the end of the procedure, could lead to unforeseen complications when vacuum is reapplied if the CCIs are not watertight (although this did not occur within the trial) (F. S. Lau et al., 2017). Furthermore, long term IOL tilt or decentration were not evaluated, but would be a theoretical risk, considering the architecture of the capsular bag is altered before its fibrotic contraction in the postoperative period. However, an in vitro study on cadaver lens capsules did not demonstrate a difference in the post-operative fibrotic response, either by growth of lens epithelial cells or quantity of fibronectin, actin or collagen type I (Wetheimer et al., 2018).

1.4.3.8. META-ANALYSES AND REVIEWS

A meta-analysis of FLACS vs CPS RCTs performed by Chen et al, identified 9 RCTs (Xiaoyun Chen et al., 2015). Overall, they found that FLACS significantly reduced EPT compared to CPS. This did not translate into a difference in central corneal thickness or endothelial cell count at one week or beyond. The rates of surgical complications were similar. The post-operative corrected visual acuity was statistically superior in FLACS at 1 week and 6 months post-operatively but not at 1-3 months. There was no statistically significant difference in uncorrected visual acuity at any time point.

A 2016 Cochrane Review analysed data from 16 RCTs including 1638 eyes. They rated all RCTs as having an unclear or high risk of bias with 11/16 authored by investigators with financial links to the manufacturer of the laser used. Due to the low level of evidence, they concluded, ‘There is currently not enough evidence to determine the benefits and harms of laser-assisted cataract surgery compared with standard ultrasound cataract surgery. The evidence is uncertain because current studies have not been large enough to provide a reliable answer to this question’ (Day, Gore, et al., 2016).

A 2016 meta-analysis of RCTs and cohort studies found no difference between FLACS and CPS in terms of unaided or corrected visual acuity or refractive outcomes. FLACS was found to be beneficial in terms of EPT, ECL and post-operative central corneal thickness (CCT) but appeared to have a greater rate of PCR (Popovic et al., 2016).

1.5. Rationale for proposed study

The average number of cataract cases performed on one NHS ophthalmic theatre half-day long list/session (3.5 - 4 hours) is unknown. ‘Action on cataracts’, published in 2000, estimated the average to be between 6 and 7.(The Royal College of Ophthalmologists, 2000) The report stated that a benchmark of half an hour per case was a reasonable expectation. 15 years after the report, 6 cases on a theatre list remains typical. Due to the ubiquitous nature of cataract surgery, any gains in operational efficiency may have far reaching consequences. For example, if the average number of cataract operations were to be permanently increased from 6 to 7 per session this would represent a 17% increase in productivity. These theatre lists act as a source of income to the hospital as the NHS trust is reimbursed a fee for all operations performed. The current tariff for cataract surgery in 2015-2016 was £718 plus an additional market forces factor.(Department of Health, 2015b) Adding more cases to a theatre list creates more revenue, yet the overhead costs will remain largely similar and are unlikely to increase by as much. By improving efficiency of the running of the theatre, the hospital can provide more value for money to the NHS.

The femtosecond laser can perform the 4 steps of cataract surgery (corneal incisions, arcuate keratotomies, capsulotomy and nucleus fragmentation) in less than one minute leaving only removal of lens fragments and insertion of the IOL to be performed by the surgeon. The potential benefits of automating several steps of the cataract operation may include better visual outcomes through greater precision and improved safety. These systems are expensive, both in the initial purchase and also the running costs, however to date the current highest level of evidence available shows no advantage in terms of safety of one method over the other hence the very limited adoption by the NHS so far (Day, Gore, et al., 2016). Despite these obvious costs, the laser removes several steps of the cataract extraction from needing to be performed by a trained surgeon, and from needing to be performed in an operating theatre (OR). In a hub and spoke model with the FL application being performed outside the OR and then feeding cases into multiple ORs, there is the potential to improve productivity and patient throughput in the operating theatre. By reducing the amount of time each patient spends in the actual OR, the volume of surgical cases may be increased per given time. If the number of cases within one theatre session can be increased sufficiently then the initial expenditure and additional costs associated with FL technology might be offset. The extra efficiency required to offset these costs remains unknown and is the focus of this research.

This thesis centres on the introduction of a FL to an inner-city teaching hospital cataract service to better understand its possible role within public health service high volume cataract surgery. Time motion studies of cataract lists and hypothetical financial modelling were completed before its introduction. The learning curve of 3 surgeons previously unfamiliar with this technology was studied in the lead up to a randomised clinical trial. A randomised controlled trial was designed which aimed to further resolve uncertainty about the clinical differences of femtosecond laser assisted cataract surgery (FLACS) compared with CPS. Within this trial, the cataract service was run as high-volume model involving the use of a FL as part of a hub-and-spoke model. The efficacy of such a service had not been previously evaluated in the peer-reviewed literature. Efficiency parameters of both the FLACS and CPS services were evaluated and used as inputs for a hypothetical financial model examining the cost of FLACS within the NHS. Clinical parameters including vision related outcomes, rates of complications, patient reported outcome measures (PROMs) and management of corneal astigmatism were recorded to ensure that there was no difference in clinical outcome or patient perceptions between the two groups. The primary hypothesis was to test whether FLACS can improve theatre efficiency sufficiently to offset the initial cost of the machine, with no disadvantage to the patients in terms of poorer clinical outcomes or patient satisfaction, and therefore comment on its possible function within public health cataract services.

Chapter 2. Time and motion studies of National Health Service Cataract Theatre lists to determine strategies to improve efficiency.

Supplementary material #1. Roberts, H., Myerscough, J., Borsci, S., Ni, M., & O'Brart, D. P. S. (2017). Time and motion studies of National Health Service cataract theatre lists to determine strategies to improve efficiency. British Journal of Ophthalmology, bjophthalmol–2017–310452–10. http://doi.org/10.1136/bjophthalmol-2017-310452

2.1. Introduction

With current financial constraints, the increased future demand for cataract surgery within the NHS is liable to be problematic. Meeting an ever-greater demand with a constrained budget requires an improvement in efficiency while, ensuring that standards of patient care are maintained or improved. A recent report from Monitor (Department of Health) estimated that 13-20% productivity gains might be made in elective ophthalmology if practices were optimized (Monitor, 2015a). The recently published *The Way Forward* report, found a median of 7 cases scheduled per theatre list (Range 4-12) (Royal College of Ophthalmologists Cataract Surgery Commissioning Guidance Development Group, 2017), which represents an almost three-fold difference in productivity between minimum and maximum values. Why this three-fold difference in productivity between minimum and maximum values exists in public sector cataract surgery has not received the due attention it should.

In 1911, F.W. Taylor introduced the time and motion study (TMS) as an application of the scientific method to the management of workers to improve productivity. Historically, TMS was applied to the manufacturing industry. However, it is has also been shown to have useful applications within healthcare (Burke et al., 2000; Finkler et al., 1993). A century after the introduction of scientific management method, there is genuine interest in aggregating knowledge in healthcare workflow, inefficiencies, patient safety and quality. Among several approaches commonly used to date, TMS, which involves continuous and independent observation of clinicians' work, is generally regarded as a more reliable methodology compared to alternative approaches such as work sampling and time efficiency questionnaires (Burke et al., 2000; Finkler et al., 1993).

To provide a quantitative assessment of the efficiency of cataract surgery across several UK hospitals, a TMS investigation was conducted at several different institutions and settings. These included: weekend waiting list initiative sessions, the provision of NHS cataract surgery in the private sector, as well as routine cataract surgery lists in NHS hospitals. Focus was placed on surgical time, surgeon tasks within and outside theatre, patient throughput, staffing levels of allied health care professional (AHPs) and their key tasks and timings. By analysing these variables and investigating correlations between them, it was hoped to provide greater awareness of different models of practice, to identify important factors leading to differences in the individual number of cataract operations per theatre session and provide information to improve surgical productivity while maintaining high levels of patient safety. To my knowledge, there are no previous examples of such TMS investigations of cataract surgery with a public health setting in the literature.

2.2. Methods

Continuous observation TMS of 18 routine four-hour cataract theatre sessions, was undertaken in 5 different hospitals and settings. These settings included two district general hospitals, two teaching hospitals, a weekend waiting list initiative theatre session in an NHS hospital, a dedicated high-volume theatre list in an NHS hospital and an NHS cataract surgery list in a private hospital (Table 2.2-A). The five institutions studied were the BMI Southend Private Hospital, Norfolk and Norwich NHS Foundation Trust, Guy's & St Thomas' NHS Foundation Trust, Southend University Hospital NHS Foundation Trust and West Suffolk NHS Foundation Trust. A consultant ophthalmic surgeon or associate specialist performed all lists, no lists were designated teaching lists. All patients were listed for only routine cataract surgery and all surgeries were conducted by phacoemulsification with intraocular lens insertion under local anaesthesia. All cases were unilateral. The number and type of AHPs supporting each individual theatre list was recorded (Table 2.2-A).

Each list had been observed prior to undergoing TMS investigation to identify preliminary staffing models and tasks (Table 2.2-A and Table 2.3-A). Agreement analysis was used to define the list of tasks and then a basic model for each setting was set up and used as a template to observe and time the steps of every defined task (table 2). Each list was observed by one or two ophthalmologists. Each observer used a template Excel spreadsheet (Microsoft Corp, Redmond, WA) with specifically designed macros to facilitate the prompt and accurate recording of tasks and their timings.

Institution	1.	2.	3.	4.	5
Type of theatre list studied	Routine theatre list	Routine theatre list	Routine theatre list Weekend initiative list Dedicated high volume list	Routine theatre list	NHS patients receiving surgery at adjacent private institution
Number of sessions observed	4	4	2 2 2	2	2
Median number of operations scheduled / list	6	6	7.5 9 13.5	7	13
Total number of cases studied	23	22	14 16 27	12	26
Percentage of operations cancelled on the day (%)	4.2%	8.3%	6.67% 11.1% 0	14.3%	0
Allied health care professionals	3 nurses	3 nurses, 1 HCA	3.5 nurses, 1 ODP 3 nurses, 1 HCA 4 nurses, 1 HCA, 1 ODP, 1 medical secretary	3 nurses	2 nurses, 1 HCA, 1 ODP

Table 1.4.3-1. Details of cataract theatre lists studied. (HCA = Health care assistant. ODP = Operating Department Practitioner)

Noting the start and finish times of some of the key tasks was self-explanatory, while other tasks required specific moments agreed upon in advance to maintain reproducibility. Surgical start and end times were regarded at the point of insertion or removal of lid speculum. Patient entry time was defined as the time from patient entry into theatre until final positioning for surgery had been achieved. Patient exit time was defined as the time from removal of lid speculum to patient exiting the theatre. Start and end of scrubbing were regarded as the opening of the tap and finishing the gowning process. The start and end of the safety checklist were recorded once the first member of staff began speaking until the last member of staff had finished speaking. The start of the scrub nurse clearing up from the case was the time when the first instrument was passed out or dismantled once the lid speculum had been removed. The end of clearing time was recorded once the scrub nurse re-entered the theatre from the sluice, having disposed of all equipment and waste. The cause and duration of any unexpected delays greater than 5 minutes were recorded.

In addition to defining each key task and its reproducible start and finish, a series of quotients were defined as follows and produced for each setting. The efficiency quotient was defined as the proportion of time that the surgeon was engaged in a task (total surgeon time spent productive/total time(Gavin C Harewood MD et al., 2008). The surgery quotient was defined as the proportion of time that surgery was occurring (total surgical time/total time). The theatre utilisation quotient was defined as the utilisation of the maximum available theatre time (time between start of first and end of last case/4 hours) (Weinbroum et al., 2003).

2.2.1. Statistics

Data is presented as non-parametric and parametric as appropriate. Differences between the groups were analysed with analysis of variance (ANOVA) one-way test where appropriate. Linear regression models were calculated to estimate the key factors effecting the time to perform the surgery, and the time an individual patient spent in theatre. Descriptive statistics was used to calculate averages and standard deviation of the performances in each list. IBM SPSS Statistics for Windows (Version 22.0. Armonk, NY: IBM Corp) was used to perform the analysis.

2.3. Results

TMS of 140 individual cataract operations were prospectively recorded during 18 NHS cataract theatre sessions. All cataract operations were performed with phacoemulsification. All operations were under local anaesthesia. All operations were unilateral. No operations were combined procedures or required additional procedures outside small-incision phacoemulsification cataract extraction and intraocular lens insertion. The details of each theatre session can be seen in Table 2.2-A.

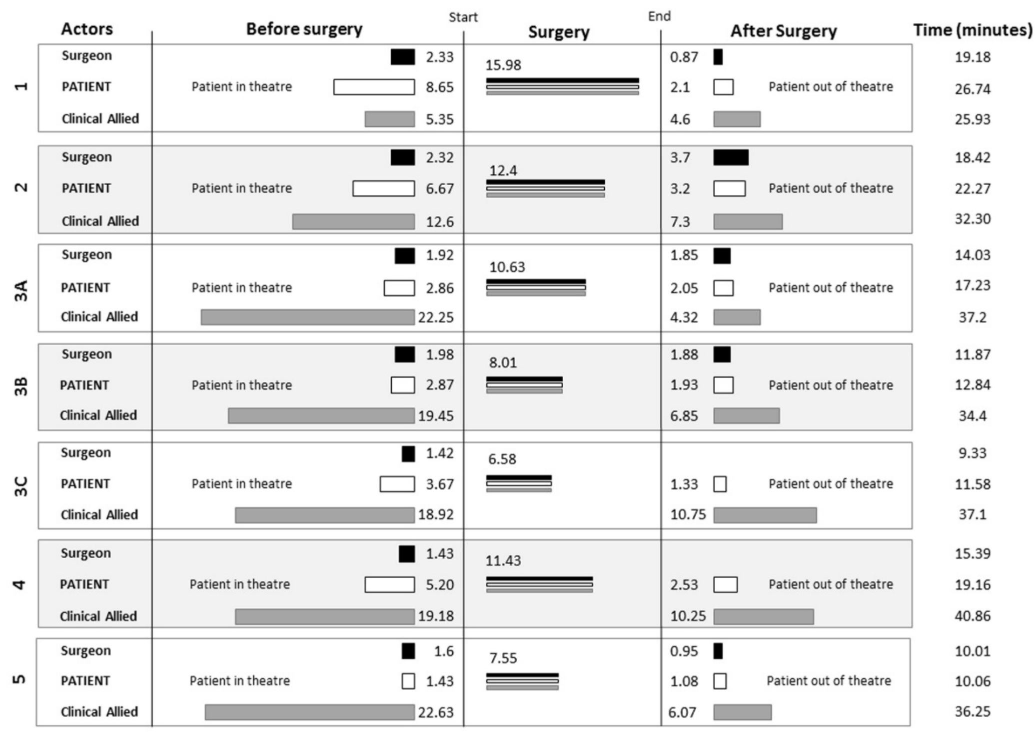


Figure 2.2.1-A Diagram of model summarizing the results of the time motion studies

Timings from each theatre list can be seen in Table 2.3-A and Figure 2.2.1-A. The reason and duration of any unscheduled delays can be seen in Table 2.3-B. Mapping of the workflow of the 2 highest volume theatre lists can be seen in Figure 2.2.1-B and Figure 2.2.1-C.

The median number of operations per 4-hour theatre session was 7 (range 5 - 14). The mean time to perform a cataract operation was 10.3 minutes (min) (standard deviation (SD) 4.11 min). The mean time to complete one case including patient turnaround was 19.97 min (SD 8.77 min). The mean surgical scrub time was 1.86 min (SD 0.77 min). The mean time to complete preprocedure WHO checklist was 0.55 min (SD 0.52 min). The mean time to complete post procedure paper/computer work was 1.77 min (SD 1.35 min). The mean time for patients to enter theatre to being positioned for surgery was 2.28 min (SD 1.88 min). The mean time from patient entry to start of operating was 4.56 min (SD 1.49 min). The mean time for patient to exit theatre from removal of lid speculum was 1.90 min (SD 1.00 min). The mean duration of patients' time in theatre was 17.07 min (SD 7.30 min). The mean time in between cases was 4.12 min (SD 2.78 min). The correlations of the surgical time to patient time in theatre was R^2=0.95. The correlation between surgical time and number of cases scheduled was R^2 = 0.696.

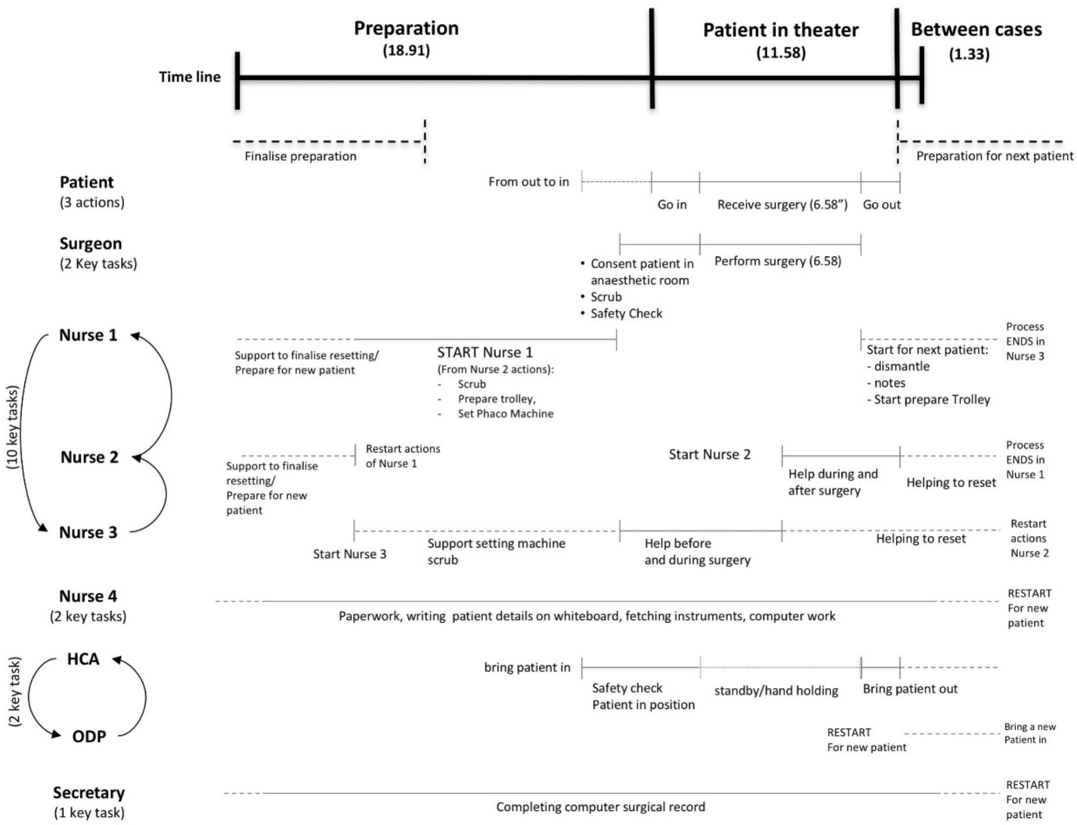


Figure 2.2.1-B Model of workflow of staff duties at Institution 3C

The minimum number of AHPs (nurses/health care assistants/operating department practitioners) allocated to a theatre list in this study was 3. The majority of AHPs in this study were registered nurses. The two theatre lists with the greatest number of cases scheduled had either 4 or 7 AHPs (Table 2.3-C). There was a moderate correlation between number of AHP and number of cases scheduled (R^2=0.489). If only the public healthcare settings were included (institutions 1, 2, 3A, 3B and 3C and 4) and one private institution was excluded (institution 5), where practices may differ from the NHS, the correlation between number of AHP and number of cases scheduled was much higher (R^2=0.823).

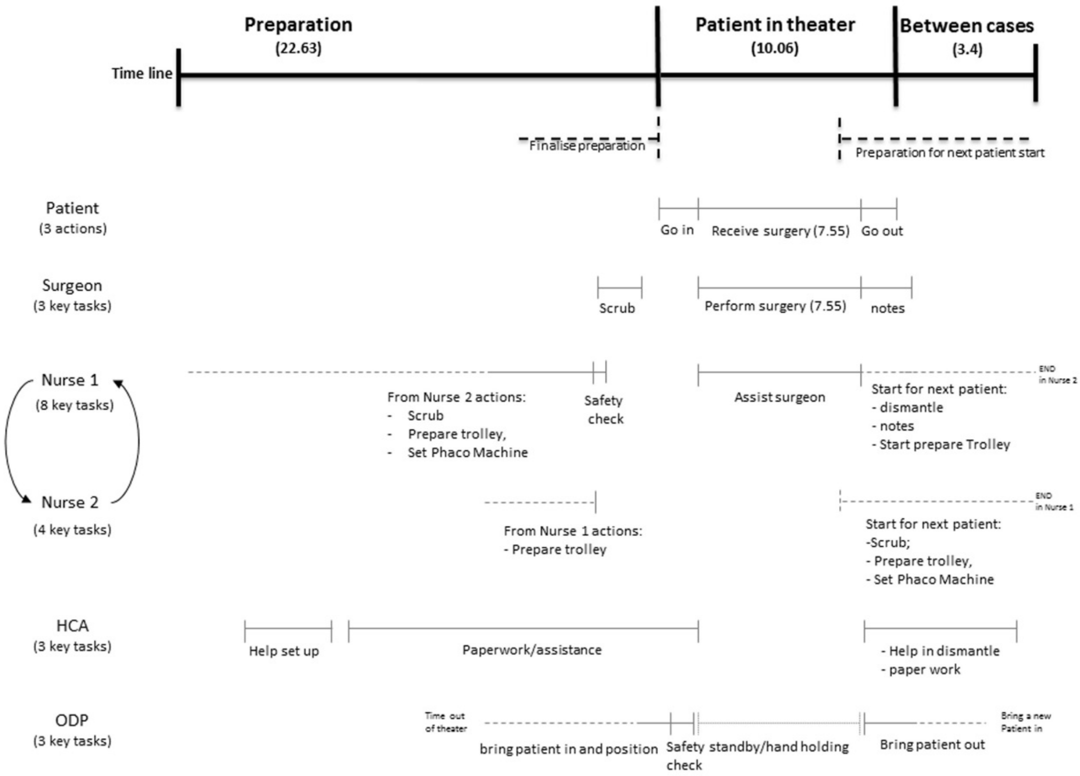


Figure 2.2.1-C Model of workflow of staff duties at Institution 5

Institution	1	2	3A	3B	3C	4	5
Average time of surgery utilized per session (range)	172.7 (160.03, 180.1)	160.97 (142.61, 176.7)	169.23 (163.87, 174.6)	163.13 (142.7, 182.57)	198.5 (185, 212.3)	122.35 (110.53, 134.17)	210.92 (194.5, 247.33)
Theatre utilization quotient	71.7%	67.1%	70.4%	67.9%	82.7%	50.8%	87.9%
Theatre utilization quotient (assuming no cancellations)	*74.8%*	*73.2%*	*75.4%*	*76.4%*	*82.7%*	*59.3%*	*87.9%*
Efficiency Quotient	66.0%	65.2%	66.4%	71.9%	76.1%	65.6%	75.8%
Surgery Quotient	53.2%	42.4%	44.0%	42.9%	52.9%	56.1%	56.7%
Average patient time in theatre (S.D.)	26.74 (5.13)	22.27 (5.1)	17.23 (2.77)	12.84 (2.32)	11.88 (1.4)	19.16 (4.96)	10.06 (4.13)
Average time between cases (S.D)	3.75 (1.98)	7.1 (3.67)	6.17 (2.43)	4.9 (56)	1.53 (0.7)	1.4 (1.12)	3.4 (1.4)
Average time from patient entering theatre to start of operation (S.D)	8.65 (3.12)	6.67 (2.72)	2.86 (1.18)	2.87 (0.58)	2.45 (2.2)	5.25 (1.98)	1.43 (0.88)
Average time for patient to exit theatre after operation (S.D.)	2.1 (1.1)	3.2 (1.03)	2.05 (0.65)	1.93 (0.4)	1.25 (0.3)	2.53 (1.03)	1.08 (0.48)
Average surgical time (S.D.)	15.98 (3.93)	12.4 (2.8)	10.63 (2.53)	8.1 (0.6)	7.43 (1.47)	11.43 (2.61)	7.55 (3.38)
Average time surgeon spends on paperwork (S.D.)	0.87 (0.37)	3.7 (1.45)	1.85 (0.93)	1.88 (0.62	0	0	0.95 (0.42)
Average surgeon scrub time (S.D)	2.33 (0.75)	2.32 (1.1)	1.92 (0.57)	1.98 (0.78)	1.43 (0.4)	1.43 (0.37)	1.6 (0.53)
Average nurse scrub time (S.D)	2.4 (0.8)	2.13 (0.7)	3.77 (1.28)	2.85 (0.97)	2.95 (0.33)	2.4 (1.07)	1.47 (0.8)
Average nurse time to prepare scrub trolley (S.D)	4.98 (1.55)	4.1 (1.4)	7.95 (0.88)	8.03 (1.72)	7.17 (1.5)	5.6 (1.9)	5.27 (1.53)
Average nurse time to prepare phacoemulsification machine (S.D)	2.72 (2.72)	4.18 (1.8)	3.15 (1.05)	2.82 (0.65)	2.6 (0.65)	3.9 (1.37)	2.07 (0.8)
Average nurse time to clear equipment (S.D)	3.68 (0.68)	3..48 (1.07)	5.35 (1.53)	4.93 (1.47)	6.37 (1.03)	7.5 (2.08)	3.48 (2.07)
Average time spent on WHO checklist (S.D)	0.65 (0.27)	0.67 (0.17)	0.7 (0.27)	0.45 (0.15)	0.27 (0.1)	0.52 (0.18)	0.73 (1.08)
Total number of key tasks performed by AHP per case	11	11	12	12	15	12	18
Average time taken to complete key tasks by AHP per case (S.D)	9.95 (6.56)	19.9 (4.15)	26.57 (2.3)	26.3 (3.15)	29.67 (3.44)	29.43 (4.89)	28.7 (6.1)
Average scheduled team break time	Nurses - staggered break, no break for surgeon	Nurses - staggered break, no break for surgeon	14.72	18.2	20.5	No breaks (relatively short theatre session)	37.8

Table 2.2.1-1 Task durations in minutes from common tasks across the institutions studied

Institution 1		Institution 2		Institution 3B		Institution 5	
Reason for delay	**Time**	**Reason for delay**	**Time**	**Reason for delay**	**Time**	**Reason for delay**	**Time**
Waiting for next patient from day case unit	5.88	Instrument error	6.52	Patient vasovagal episode	10.3	Waiting for next patient from day case unit	6.0
Surgeon examining staggered patients	9.5	Equipment error	5.17			Waiting for next patient from day case unit	5.75
Waiting for next instrument trolley to be ready	7.43	Surgeon required to see patient in clinic	13.23				
Surgeon out of theatre	8.75	Surgeon late for theatre due to clinic overrun	28.17				
Surgeon examining staggered patients	08.32	Surgeon reviewing latecomer	7.35				
		Waiting for next patient from day case unit	10.5				
		Waiting for next patient from day case unit	8.95				
Total	**39.88**		**79.88**		**10.3**		**11.75**

Table 2.2.1-2 The reason and duration, in minutes, of any unscheduled delays

Setting	Number of allied health professionals	Median number of cataracts scheduled/session
1	3	6
4	3	7
2	4	6
3A	4.5	7.5
3B	4	9
5	4	13
3C	7	13.5

Table 2.2.1-3 Staffing levels associated with number of cases scheduled

2.3.1. Multiple linear regression models

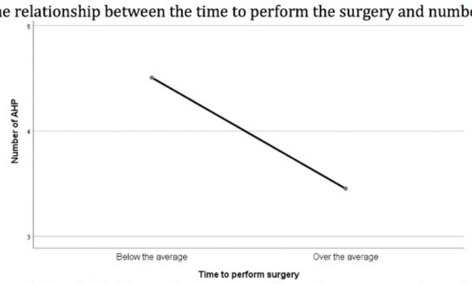
A multiple linear regression model was calculated to predict the time to perform one operation based on three factors: i) the number of AHPs, ii) the number of key tasks performed by AHPs and iii) time taken to perform these key tasks by AHPs. A significant regression was found ($F(3,111) = 32.86$ $p<0.001$) with an R^2 of 0.47. All the three factors were significant predictors of the time to perform a surgery. The surgical time decreases by 0.95 min for each additional AHP involved, by 0.39 min for every additional task performed by AHP, and by 0.19 min for each additional minute spent by AHP performing tasks.

An ANOVA-one way was performed to control for the effect on surgical time by: i) the number of AHPs, ii) the number of key tasks performed by AHPs and iii) time taken to perform these key tasks by AHPs. There was a significant effect ($p<0.001$) of all the factors as follows: i) $F(1,113) = 35.12$, $p=0.001$), ii) $F(1,113)=53.43$, $p=0.001$); iii) $F(1,113)=42.23$, $p=0.001$) (Figure 2.3.1-A).

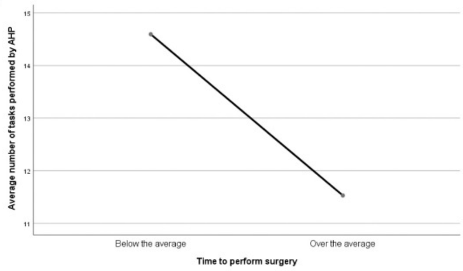
A similar multiple linear regression model was calculated to predict the effect of the same three factors i) the number of AHPs, ii) the number of key tasks performed by AHPs and iii) time taken to perform these key tasks by AHPs on the total patient time in theatre. Factors ii and iii were significant predictors of the time an individual patient spent in theatre i.e. the total time to complete one surgical case. The model was significant ($F(2,116) = 43.18$ $p<0.001$) with an R^2 of 0.43. The length of patient time in theatre decreased by 0.76 min for each task performed by AHPs and by 0.19 min for each minute spent by AHPs to perform their tasks.

An ANOVA-one way was performed to control the effect on the total patient time in theatre by i) the number of AHPs, ii) the number of key tasks performed by AHPs and iii) time taken to perform these key tasks by AHPs. There were significant effects of factors ii and iii ($F(1,117)=43.97$, $p<0.001$)(Figure 2.3.1-A).

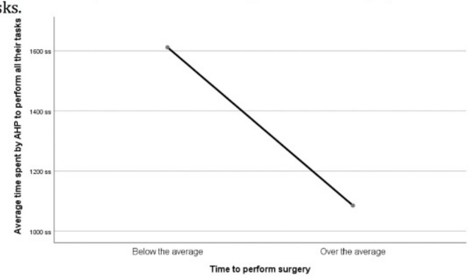
Section A: shows the relationship between the time to perform the surgery and number of AHPs.



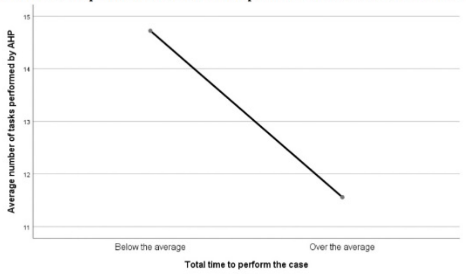
Section B: shows the relationship between the time to perform the surgery and number of tasks performed by AHPs.



Section C: shows the relationship between the time to perform the surgery and the time spent by AHPs to perform their tasks.



Section D: shows the relationship between the time to perform the case and number of AHPs.



Section E: shows the relationship between the time to perform the case and the time spent by AHPs to perform their tasks.

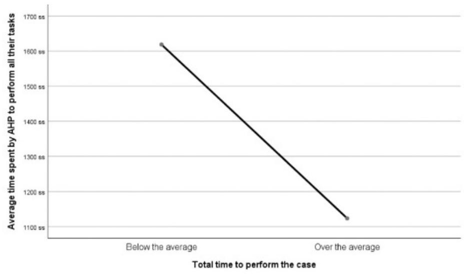


Figure 2.3.1-A Represents the significant relationships identified by ANOVA. The average time to perform the surgery was equal to 10.25. The average time to perform the case was equal to 14.08. Section A: shows the relationship between the time to perform the surgery and number of AHPs. Section B: shows the relationship between the time to perform the surgery and number of tasks performed by AHPs. Section C: shows the relationship between the time to perform the surgery and the time spent by AHPs to perform their tasks. Section D: shows the relationship between the time to perform the case and number of AHPs. Section E: shows the relationship between the time to perform the case and the time spent by AHPs to perform their tasks.

2.4. Discussion

This study adopted a TMS approach to evaluate the efficiency of public sector cataract surgery in the UK. A significant variance in the running of cataract theatre lists at five different UK institutions was observed, the most striking of which is the number of patients scheduled per list, which ranged from medians of 6 to 13.5. From the perspective of the public healthcare sector, it is imperative to maximize the efficiency of elective surgery while maintaining quality and safety(Monitor, 2015a). The average duration of a cataract operation was 10.3 min and the total time including pre- and post- procedure preparation and patient turnaround was 19.97 min. It could be expected therefore that at least 12 operations could be completed in a 4-hour session and yet the median number of cases booked to a theatre list of 7 is much less. Based on the results of this TMS, one could expect that an increase in 70% efficiency might be possible. Whether this is an achievable target and why it is not currently being realized is a matter of conjecture, but certainly it highlights the great need to identify possible factors necessary to improve the efficiency of NHS cataract surgery.

It was interesting to document that the sessions (institutions 3C and 5) providing the highest median number of cases per list (13, 13.5) and highest theatre utilization and efficiency quotients, had the longest duration of staff breaks, suggesting that these units have discovered how to 'work smarter, not harder' (Table 2.3-A, Figure 2.2.1-A, Figure 2.2.1-B, Figure 2.2.1-C). This strongly suggests that by changing working practices efficiency can be improved without increasing individual staff workload.

This assumption is supported by the observation that institutions 4 and 5 share the same population, yet there are noticeable differences between the TMS of their theatre sessions, especially in terms of median number of cases per list (7 versus 13), theatre utilization quotient (50.8% versus 87.9%) and efficiency quotient (65.6% versus 75.8%) (Table 2.3-A). As patient demographics should be similar at these two settings, differences in practice and efficiency presumably arise from internal organization of the cataract theatre lists rather than external factors.

In considering the TMS of the surgeons, it is important to recognize that the theatre session is not an independent entity. Rather, differences in theatre practices often stemmed from factors outside the theatre itself, such as in the day case ward/clinic. For example, at institutions 1 and 4, the surgeons performed slit-lamp examination and marked all patients on the day of surgery, at institution 2 the surgeon met the patients and marked them, at 3A/B/C the surgeon met the patient, marked and consented them, while at 5 (which had the highest theatre utilization quotient and second highest median number of cases at 13) all such tasks were performed by staff on the day-case unit. This suggests that utilizing AHPs to undertake some of the duties of the surgeon outside theatre, might be an important factor in improving efficiency by ensuring that the surgeon spends as much in theatre as possible during each allocated 4-hour cataract surgery session. This is supported by the observation that institution 1 (with a joint lowest median number of cases of 6 and an efficiency quotient of only 66%) was the only unit in which there was both staggered patient arrival and surgeon performing pre-operative examination, leading to the surgeon leaving the theatre for 26.57 min out of theatre during the 4 hour sessions (Table 2.3-A and Table 2.3-B). Similarly, at institution 2 (joint lowest median number of cases of 6 and efficient quotient of 65.2%), the surgeons spent 48.75 min outside the operating theatre due to out-patient clinic overrun and the need to see additional patients on the day case ward (Figure 2.2.1-A, Table 2.3-A and Table 2.3-B). Clearly to achieve optimum efficiency it is imperative for the surgeon to be available within theatre to undertake the surgery rather than performing duties outside. Whether this is best achieved by AHPs performing such outside duties instead of the surgeon as at institution 5, or ring-fenced time before the theatre session itself is a matter of conjecture.

Some units allowed patients to arrive on a staggered basis for their convenience and reduced overall patient waiting time (institutions 1, 3A/B/C, 5), while the remainder requested that all patients were present for the pre-theatre ward round. As such practices did not affect the overall median number of cases or efficiency quotients (Table 2.3-A), it seems a reasonable approach to stagger arrival times for patient convenience, provided protocols are introduced to avoid surgeons spending time out of theatre, as at institution 1.

Based on the observations of this current study, a minimum of 4 AHPs appear to be required to provide a high-volume service. This criterion was met at all settings other than institutions 1 and 4 (Table 2.3-C). Increasing the number of cases towards the goal of high volume lists may require either/both an increase in the number of AHPs supporting the surgeon with additional tasks (as in setting 3C) or changes in working practice (as in setting 5), with 4 AHPs performing more supporting tasks. It appears that in addition to the scrub nurse and circulating AHP, at least two AHPs are required to be able to clear up from the previous case and, more importantly, prepare for the subsequent case so there is only a minimal wait between cases. This is achieved at institutions 3C and 5 (this lists with the highest volumes of patients treated per session) with 18.92min and 22.63min of total AHP preparation time respectively before the patient even enters theatre (Figure 2.2.1-B and Figure 2.2.1-C). Ideally, the gap between cases needs to be minimized to the time it takes to escort the patient out and in, perform the WHO checklist, and for the surgeon to rescrub. In this series, the length of time from the end of one case to the start of the next ranged from 5.92 to 16.8 min.

Between the institutions the average surgical time varied from 7.43 to 15.98 minutes. This variation may reflect different case mix or differences between surgeons with some being faster than others or using more efficient equipment, such as the phacoemulsification machine. The surgeons in lists 3C and 5 have a national reputation of excellence and are known for their expertise and surgical skills and this may have created outlying results. However, despite this the correlation between AHP numbers and tasks was strong and means that efficiency can be improved for those that do not have exceptional surgical skills. The correlation between surgical time and number of cases scheduled was R^2 = 0.696, suggesting that factors such as surgical experience and case mix are likely to have a part to play in cataract surgery efficiency. However, a significant correlation was found in this study between the time undertaken to perform cataract surgery and the number of AHPs, the number of key tasks performed by AHPs and the time taken to perform these key tasks by AHPs ($p<0.001$). This was confirmed by ANOVA one-way testing, suggesting that alteration of the number of AHPs supporting a cataract surgery list and surgeon, their duties and their total time performing tasks, is strongly associated with and can indeed influence the time to perform individual cataract surgery (Figure 2.3.1-A).

Similarly, a strong correlation, confirmed by ANOVA one-way testing, was found between the number of key tasks performed by AHPs and the time taken to perform these key tasks by AHPs on the total patient time in theatre ($p<0.001$). Such correlations appear to high-light the importance of AHPs and their designated tasks in the development of high volume NHS cataract surgery.

Concerning institution 5, which appeared to be an outlier in terms of correlation of number of AHPs with efficiency, these results might be explained by the fact that this was a private institution with different working practices from public health sector settings and there were direct financial incentives for the numbers of patients treated which it could be assumed positively influence productivity. Most importantly, whilst the number of AHPs supporting the cataract theatre list at institution 5 was 4, the number of key tasks performed by AHPs per case was much higher at 18 than any other organization (Table 2.3-A). At institution 5, it clearly appeared that AHPs were undertaking many of the tasks performed by the surgeons at other institutions, which ensured that the surgeon was spending far more time in theatre undertaking surgery than at any other institution. As such this unit could optimize surgical productivity and theatre utilization. Indeed, the results at institution 5 strongly support the correlations concerning the importance of AHPs, their roles and tasks they undertake, in optimizing cataract surgical list efficiency. It appears that expansion of the role of AHPs in the public-sector health setting to incorporate some the non-surgical roles currently undertaken by the surgeon, as well as the maintenance of adequate AHP staffing levels is vital to optimize cataract surgery efficiency.

There was generally an under-utilization of the full 4-hour (240 min) theatre session. Average theatre utilization was 70.11% (range 50.8% to 87.9%) and was 73.9% (range 59.3% to 87.9%) when extrapolated to consider the cancelled operations. The reasons for delayed start of theatre sessions included the surgeon being delayed by an overbooked clinic or administrative duties on the day case ward (table 3). Pre-operative examination of surgical patients and associated duties (patient marking, confirmation of consent, etc.) is an integral part of the surgical process, but duration should be minimized to maximize potential surgical time. However, in the interests of patient safety, it is not suggested that the target for theatre utilization should be 100% due to the possibility of a case taking longer than expected or the event of a surgical complication, albeit the risks of surgical complications in cataract surgery is generally low (<5%) (Day, Donachie, et al., 2015).

The current study does have several limitations. Firstly, it focused on single independent consultant or associate specialist surgeon theatre sessions and not on training lists with junior doctors. Ophthalmic specialist trainees are known to take longer to perform cataract surgery than experienced consultants (Park et al., 2016). Clearly there is a need to balance the desire for high volume services and the promotion of high quality provision of training for the next generation of surgeons. However, if sufficient high volume can be achieved in single surgeon lists, this can reduce the pressure of service-provision demands in training lists. Indeed, given the increased future demand for cataract surgery within the NHS (Chapter 1), there is a great need for senior trainees as future consultant surgeons to have exposure to high volume models of cataract surgery.

Secondly, observations were made based on a relatively small number of observed sessions (eighteen). To our knowledge this is the first TMS of its kind in cataract surgery. TMS are, by their nature, very labour intensive. Historically, TMS would often require one observer for each person studied which would, of course, introduce great difficulty (logistical and financial) in studying a cataract theatre session. It was found that through the use of Macros on Microsoft Excel, timings for all staff involved with a theatre session could be recorded with only two observers. This study represents the first example of TMS of cataract theatre sessions published, which is of importance, especially in understanding differences in productivity within state-funded healthcare systems. Clearly, however, there is scope for future research incorporating greater numbers of operations at more institutions which may facilitate analysis of a greater number of factors and less risk of chance findings.

It is also of note, that results from the five hospitals participating in this study, incorporated a mixture of academic centres and district general hospitals, with both rural and urban populations. They were chosen carefully to reflect a broad spectrum of environments. However, this study does not claim to represent universal provision of cataract services across the UK. We did not evaluate any different case mixes, including theatre lists with a variety of different cases or where an anaesthetist is present. However, the vast majority of cataract surgery performed with the UK is undertaken under topical/local anaesthesia (Department of Health, 2015a; Day, Donachie, et al., 2015) and the aim of this study was to focus on the delivery of high volume services, wherein general anaesthetic (GA) cases are unlikely to feature. Furthermore, it was assumed that all theatre teams were experienced with cataract theatre lists and familiar with working with each other. Indeed, during the TMS nothing was observed to the contrary.

Finally, although the focus of this study was the efficiency of cataract surgery, the metrics of the quality of the surgery, such as post-operative visual acuity, post-operative complications, post-operative refraction and patient satisfaction were not evaluated. Suggestions to changes in practice laid out in this chapter relate to improving efficiency only. It is important to remember that the quality of any aspect of cataract surgery and overall patient satisfaction should never be compromised to enhance efficiency, for example satisfaction may be adversely affected if surgeons lack sufficient time with the patient pre-operatively to establish a good rapport.

2.5. Conclusion

This current TMS study, highlights the huge variation in the efficiency of cataract surgery, within the NHS. It suggests that by providing sufficient levels of AHP staffing and expanding the roles of AHPs to minimize patient turnover time and most importantly undertake some of the non-surgical tasks currently performed by surgeons during cataract theatre sessions when ideally they should be mainly concentrating on operating, productivity in cataract surgery and theatre utilisation could be significantly improved in the public sector.

Chapter 3. Financial modelling of Femto-second Laser Assisted Cataract Surgery within the National Health Service using a "Hub and Spoke" model for the delivery of high volume Cataract Surgery

Supplementary Material #2. Roberts, H., Ni, M. Z., & O'Brart, D. P. S. (2017). Financial modelling of femtosecond laser-assisted cataract surgery within the National Health Service using a "hub and spoke" model for the delivery of high-volume cataract surgery. BMJ Open, 7(3), e013616–9. http://doi.org/10.1136/bmjopen-2016-013616

3.1. Introduction

Until better evidence exists of improved surgical outcomes it is difficult at present to support the wide-spread implementation of FLACS. This is particularly pertinent as the introduction of FLACS has significant associated financial costs. These include initial purchase costs of the FL system itself, servicing, depreciation and the individual patient interfaces (PI), which call into question its financial viability, especially in a state funded healthcare system. The majority of existing literature on the economics of FLACS originates from healthcare systems within such countries as the US or Australia, where additional costs from procedures perceived as having a premium status may be passed onto the patient in the form of a co-payment system (Abell and Vote, 2014; Hansen and Hardten, 2015; Bartlett and Miller, 2016). In these healthcare systems, the existing literature suggests that FLACS is not currently a cost-effective solution. It is not surprising therefore, that adoption of this technology within the NHS so far has been minimal and largely directed at research rather than service provision.

Despite associated costs, by its very nature the FL offers the potential to remove several steps of cataract extraction from needing to be performed by a fully trained surgeon in a fully-equipped ophthalmic operating theatre. FL technology can automate several surgical steps of the cataract procedure, such as corneal incisions, arcuate keratotomies, capsulotomy and nuclear lens division, all of which can be potentially undertaken with this technology by a doctor in training or suitably trained nurse or technician in a clean room. By reducing the actual amount of time each patient spends within the operating theatre under the care of a trained surgeon, the volume of surgical cases undertaken in a given period might potentially be increased. This may be especially true if a “hub and spoke” model is utilized, with the FL performing these initial automated steps and then allowing the completion of the surgical procedure to be undertaken in more than one operating theatre at a time. If the number of cases per theatre session can be increased sufficiently then the initial expenditure and additional costs associated with FL technology might be offset.

For FLACS to see increased adoption by a state funded healthcare system such as the NHS, it would need to be shown to be cost-effective based on an acceptable incremental cost effectiveness ratio (ICER). The ICER is defined by the difference in the cost between two possible interventions divided by the difference in their clinical effectiveness. This study aims to investigate, in the anticipation of outcomes from the subsequent RCT (Chapter 5), the cost of incorporating FLACS into the NHS system to determine whether the increased costs of equipment may be offset by an increase in the volume of surgery performed.

3.2. Methods

3.2.1. Financial Model

A financial model was designed to compare FLACS against CPS for the provision of cataract surgery within the NHS. The inputs for this model can be seen in Table 3.2-A. The model was based on data from four separate NHS Foundation Trust Ophthalmology Departments (Guy's and St Thomas' NHS Foundation Trust, Norfolk and Norwich NHS Foundation Trust, Peterborough and Stamford NHS Foundation Trust and West Suffolk NHS Foundation Trust) and four manufacturers of commercially available FL devices (Abbott Medical Optics, Santa Ana, CA; Ziemer Ophthalmic Systems AG, Switzerland; Alcon Laboratories, Inc., Fort Worth, TX and Bausch & Lomb, Rochester, NY). The data was collated and averaged to ensure the results were more representative than had just one ophthalmology department or one FL been used.

Values for each input were derived from the following sources.

i. Income for each procedure is reimbursed at the NHS national tariffs for 2014-15 plus an additional market forces factor(Department of Health, 2016b; 2016a).

ii. Costs were divided into direct labour costs, equipment costs and overheads. Direct labour costs per theatre session were derived from NHS pay scales and midpoint values were chosen. This was then proportioned to the estimated duration of each theatre session.

iii. Costs relating to the FL were averaged from those provided by four manufacturers of commercially available FL devices.

iv. Costs such as estate, equipment, and supplies were averaged from four NHS Foundation Trusts' departmental budgets (2014-15).

v. Pharmacy and administrative costs were obtained by reviewing the departmental budget at our institution.

vi. Baseline values for the number of cases achievable per 4-hour theatre session were given nominal values of 7 cases for CPS and 10 cases for FLACS. These initial values were then tested using sensitivity and threshold analyses.

The model was tested based on two scenarios: FLACS versus CPS based on an average number of 7 cases currently performed on a CPS cataract lists and a

FLACS delivery model based on a “hub-and-spoke” method with one FL in a clean room and operated by a doctor in training preparing patients for two operating theatres running in parallel with their associated surgeons, nursing and technical support staff.

3.2.2. “Hub and Spoke” FLACS model

The theoretical ‘hub-and-spoke’ model for FLACS is based on a single FL platform in a clean room and operated by an ophthalmology registrar or suitably trained allied health professional and supported by a theatre nurse (Figure 3.2.2-A). The laser would be programmed to perform capsulotomy, nuclear lens division and arcuate keratotomies (when indicated) for each individual patient. Patients would be prepared for two operating theatres running in parallel with their associated surgeons, nursing and technical support staff. The assumed FL treatment time is a maximum of 10 minutes per patient allowing for the preparation of up to 20 cataract surgery cases, 10 per theatre per 4-hour operating theatre session. The assumed theatre time is a maximum of 24 minutes per case. These values are based on our own experience with the FL.

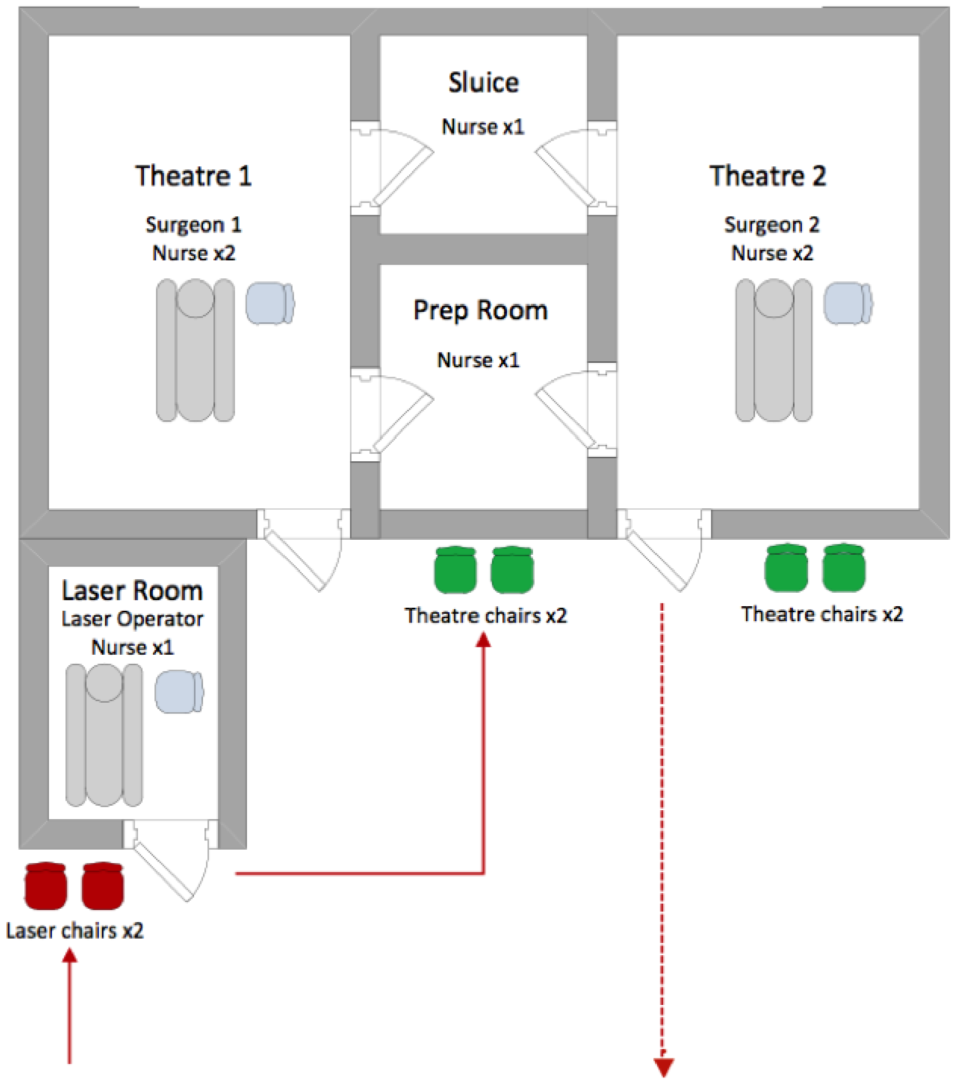


Figure 3.2.2-A A proposed 'hub-and-spoke' model for FLACS

A				
Source		**Input**	**Value (£)**	**Range (£)**
Income		NHS tariff for cataract surgery	789	729-917
Expenses	Staffing (per session)	Consultant surgeon	246	
		Band 5 nurse	79	
		Registrar/laser technician	101	
		Band 6 nurse /laser technician	102	
		Ward clerk	53	
	Overheads (per year)	Ophthalmic Day Case Unit	525,620	30,112 – 1,061,481
		2x Operating Theatres	585,676	353,245 – 962,287
	Laser	Initial cost	262,500	175k – 350k
		Maintenance/year	28,333	20k-35k
		Cost of patient interface	134.75	99-170
	Other costs	Disposables and IOL (per case)	103	
		Cost of administration, management and pharmacy (per case)	50	
B				
Other variables		Number of cataract operations required per week	55 operations	27 - 96
		Number of cases on CPS list	7 operations	
		Number of cases on FLACS list *	10 operations	
		Lifetime of FL	10 years	

*Table 3.2.2-1 Inputs for the model and nominal values * Based on the hub and spoke FLACS delivery model*

3.2.3. Sensitivity Analysis

The model was constructed using Microsoft Excel (Microsoft Corp, Redmond, WA) based on the range of the above inputs (Table 3.2-A). Uni- and bi-variate sensitivity analyses were conducted by varying the inputs into the model to simulate the impact on the final service costs. The inputs chosen for the sensitivity analysis were as follows:

i. Capital cost of the FL
ii. Cost of the PI
iii. Number of cases possible on a FLACS theatre list
iv. Number of cases performed on a CPS list

v. Number of cataract operations required per week

Threshold analyses were performed on the same variables as the sensitivity analyses to determine threshold values at which FLACS may break even with CPS. The results are reported as weekly costs.

3.3. Results

The first model tested FLACS versus CPS based on an average number of 7 cases currently performed on CPS cataract lists. Our model estimated that the current CPS service at its existing productivity was costing £433 per case. Using a model that incorporates one FL into one theatre list, and therefore assuming no increase in productivity, the laser increases the cost per case by £167 to £600. Based on these values, the CPS service would be 72% of the cost of a FLACS service.

Using the averaged and nominal values for our theoretical "hub-and-spoke" model for FLACS, use of the FL reduced the weekly theatre requirements from 8 CPS theatre sessions to 2.7 FLACS sessions with both theatres in the FL model running in parallel (total theatre sessions 5.4). This reduced the anticipated running costs of theatres, the ophthalmic day-case unit and staffing costs. However, the laser introduced additional costs into the model (FL equipment, supplies, maintenance and additional staff). Based on the nominal values, even with our hub and spoke model running optimally, the CPS service (average of £433/case) was found to be 86.3% of the cost of the FLACS service (average of £502/case).

The capital cost of the FL when amortized over its lifetime of 10 years was £505 per week (pw). Maintenance of the laser was £545pw. The cost of one week's worth of patient interfaces (n=55) at £135 each, was £7,356 (Figure 3.2.3-A).

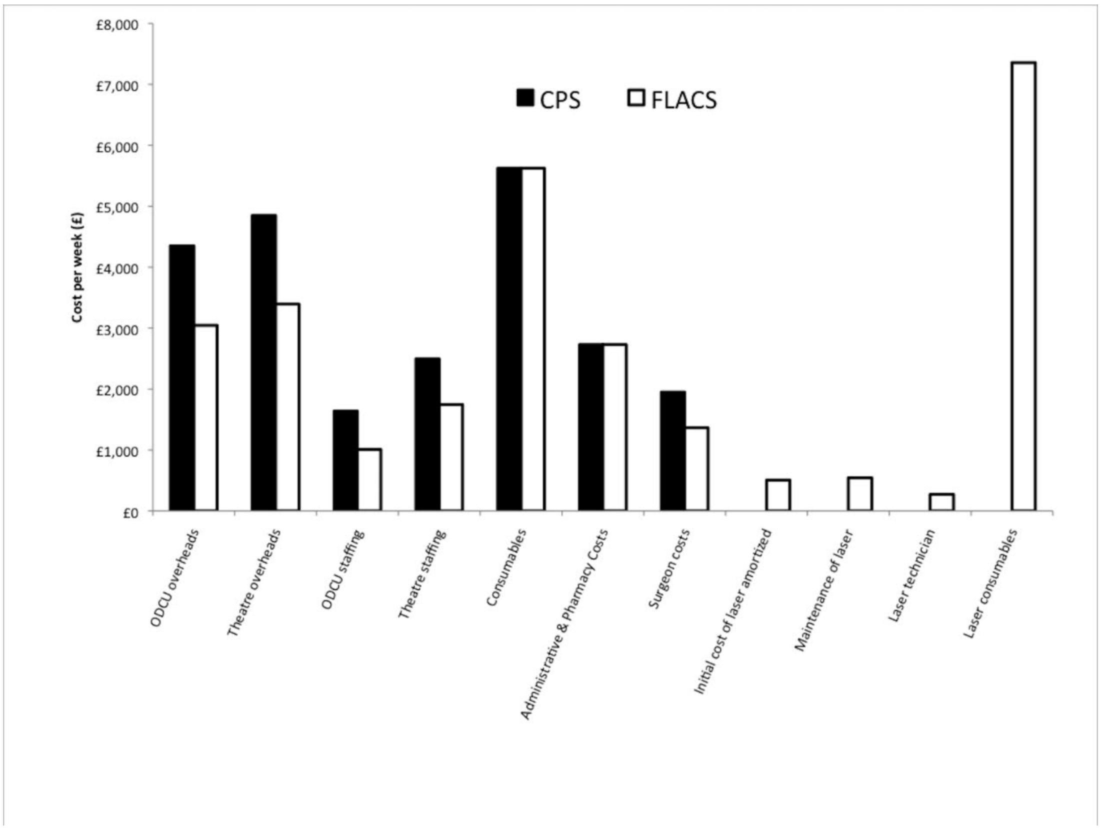


Figure 3.2.3-A Comparison of the costs per week of CPS compared with FLACS

The model was not affected when the salary of the laser operator was changed from a mid-point registrar to a band 6 nurse as the hourly rates were of negligible difference (Table 3.2-A).

Univariate sensitivity analyses were conducted by varying one variable at a time. Minimum and maximum values were obtained from the original data (Table 3.3-A). Only when the number of operations on a CPS list were reduced or the number of operations on a FLACS list were increased, could the model give an output in favour of FLACS. Best and worst-case scenarios were constructed for both CPS and FLACS, by aligning the most important variables all in favour of one or other modality, with costs of £371 and £515 for CPS and £381 and £545 for FLACS respectively (Table 3.3-A).

A

Input	**Range of values**	**Values inputted into hub-and-spoke model**	**Cost of CPS service compared to FLACS (%)**
Cataract workload/week	Minimum	27	82.7
	Average	55	86.3
	Maximum	96	87.8
Number of cataracts on CPS list*	Minimum	5	108.5
	Nominal	7	86.3
	Maximum	9	73.8
Number of cataracts on FL list**	Minimum	8	78.6
	Nominal	10	86.3
	Maximum	16	100.8
Initial cost of FL	Minimum	£175,000	86.7
	Average	£262,500	86.3
	Maximum	£350,000	85.7
Cost of PI	Minimum	£99	92.8
	Average	£135	86.3
	Maximum	£170	80.5

B

	Cataract workload /week	Number of cataracts on CPS list	Number of cataracts on FL list	Cost of PI	Cost of CPS /case	Cost of FLACS /case	Cost of CPS service compared to FLACS (%)
Best case scenario for CPS	27	9	9	135	£371	£515	72.1
Best case scenario for FLACS	96	5	10	50	£545	£381	143.2

Table 3.2.3-1 A. Univariate sensitivity analysis of the hub-and-spoke model based on range of values from data collected

**Assuming 10 cases on FLACS list*

*** Assuming 7 cases on CPS list.*

B. Best case scenarios for CPS and FLACS

Univariate threshold analyses were performed to demonstrate the 'break-even' values of each input. Keeping all other inputs at their original values, the model could not find solutions by which the FL broke even when the capital cost of the FL or the number of operations performed per week were chosen. The costs of the services were equivalent if the true number of cases on a CPS list was 6, or if the FL could increase productivity to 16cases/each theatre, or if the cost of the laser consumables were reduced to £66. It was thereby ascertained that these three parameters are the most important in this model for determining a cost-neutral scenario for FLACS.

Bivariate sensitivity analyses were performed using combinations of the above inputs. For example, Table 3.3-B shows the outcomes of the model when the capacity for number of cases on both CPS and FLACS are simultaneously tested. It shows that the FLACS service would be required to approximately double the number of operations possible during a theatre list for FLACS to break even. Table 3.3-C tests the outcome of the model based on an assumption that the NHS or a hospital trust could negotiate lower PI costs based on the provision of a large number of operations per year. It shows that FLACS cannot break even unless the cost of the PI is significantly reduced (to approximately £50 per case). Table 3.3-D compares the cost of the PI against the number of cases on a FLACS list.

	Number of operations on CPS list				
Number of operations on FLACS list	**5**	**6**	**7**	**8**	**9**
8	99.0%	87.1%	78.6%	72.3%	67.3%
10	**108.5%**	95.5%	86.2%	79.2%	73.8%
12	**115.9%**	**102.0%**	92.1%	84.7%	78.9%
14	**121.9%**	**107.3%**	96.9%	89.0%	82.9%
16	**126.8%**	**111.6%**	**100.8%**	92.6%	86.3%

Table 3.2.3-2 Cost of FLACS vs CPS. Bivariate sensitivity analysis: demonstrating relative costs of CPS service compared to FLACS when total number of cases on each theatre list are tested

	Number of cataract operations per year				
Cost of PI (£)	**2000**	**3000**	**4000**	**5000**	**6000**
50	**101.5%**	**104.0%**	**105.2%**	**106.0%**	**106.5%**
75	95.9%	98.1%	99.2%	99.9%	**100.4%**
100	90.9%	92.8%	93.8%	94.4%	94.9%
125	86.4%	88.1%	89.0%	89.6%	89.9%
150	82.3%	83.8%	84.7%	85.2%	85.5%

Table 3.2.3-3 Cost of FLACS vs CPS. Bivariate sensitivity analysis: demonstrating relative costs of CPS service compared to FLACS when cost of PI and total number of cases per year are tested

	Number of operations on FLACS list					
Cost of PI	**8**	**9**	**10**	**12**	**14**	**16**
50	92.9%	98.6%	**103.7%**	**112.4%**	**119.5%**	**125.5%**
65	90.0%	95.4%	**100.1%**	**108.2%**	**114.8%**	**120.3%**
80	87.3%	92.3%	96.7%	**104.3%**	**110.4%**	**115.5%**
100	83.9%	88.5%	92.6%	99.5%	**105.0%**	**109.6%**
120	80.8%	85.1%	88.8%	95.1%	**100.2%**	**104.3%**
135	78.6%	82.6%	86.2%	92.1%	96.8%	**100.7%**

Table 3.2.3-4 Cost of FLACS vs CPS. Bivariate sensitivity analysis: demonstrating relative costs of CPS service compared to FLACS when cost of PI and number of operations on FLACS list are tested

3.4. Discussion

A hypothetical treatment delivery model based on a “hub and spoke” service and utilizing FLACS was designed to improve the efficiency of cataract surgery in terms of number of cases undertaken per operating list. The model was then tested with sensitivity and threshold analyses to allow for variations or uncertainties.

Even with an optimized delivery model FLACS is still more expensive than CPS based on current estimates of costs. To break even, the incorporation of FLACS would have to approximately double the number of cataract operations performed per theatre list and indeed could not offer a cost-neutral solution if the number of cases on a CPS theatre list was 8 or more. The model indicates that the greatest cost impediment to a FLACS service is the price of the PI (average cost £135/case) (Figure 3.2.3-A), which represents almost 27% of the total cost per case. Unlike other service costs, the cost of the PI is not mitigated by potential increased productivity. It is therefore a major financial impediment to FLACS ever becoming cost effective within the NHS, where the total tariff for each operation is fixed between £718-932 (Department of Health, 2016b; 2016a). Potentially this problem may be overcome by the manufacturer considerably discounting this cost to the NHS. In contrast to the PI our financial model indicates that the costs of the laser itself, staffing and maintenance were much less important (4.8% of total costs).

There are three important unknowns with regards to our model. Firstly, we are awaiting clinical results from large RCTs comparing FLACS to CPS (Schweitzer et al., 2014; Day, Burr, et al., 2015). Meta-analyses shows no significant advantages in terms of safety of FLACS over CPS (Xiaoyun Chen et al., 2015; Popovic et al., 2016). However, there are advantages in terms of endothelial cell loss, effective phacoemulsification time and unaided visual acuity, albeit no difference in long-term best corrected visual acuity and an increased risk of anterior capsular tear (Kohnen et al., n.d.). It was assumed in the financial modelling that there are no differences in outcomes and complication rates between the two procedures. If, however, FLACS were to show significant advantages in terms of patient safety and outcomes then such improvements then this may have additional positive financial implications.

Secondly, potential gains in productivity from the FL are yet unpublished and unrealized. Several studies investigating FLACS report decreased patient turnover with FLACS (Abell and Vote, 2014; Bali et al., 2012; Lubahn et al., 2014). This is because at present typically the operating surgeon is performing both the FL treatment as well as the subsequent lens extraction. There are yet no publications on the most effective way to design a FL-centric cataract service. I this study a “hub-and-spoke” model based on one FL in a clean room, operated by an ophthalmic surgeon in training or ophthalmic technician/nurse was chosen. The FL then fed patients into two independent operating rooms, each with its own surgeon and support staff. This model is theoretical. It needs to be tested in the NHS setting to see if it is viable and further work may need to be done to determine a ‘best-practice’ and optimized efficiency model for FLACS.

Thirdly, it is likely that the costs of the PIs would be reduced below the values quoted to us by the manufacturers, as a large public-sector ophthalmology department performing several thousand operations per year could negotiate on costs and capitalise on market competition. As discussed above this would considerably improve the financial burdens associated with implementing FLACS.

Abell and Vote have previously designed a hypothetical model to derive cost-effectiveness of FLACS (Abell and Vote, 2014). In the absence of better evidence, conservative estimates were used for complication rates with FLACS. Their use of the FL resulted in reducing their theatre efficiency by 2 cases per list, and subsequently they estimated the additional cost of FL to be AUS$1065 per case, AUS$750 of which were the direct costs from the FL and AUS$315 from lost productivity. Our model was based upon using the laser to improve, rather than impede productivity. We estimated the additional cost per case to be £158, of which £135 is the PI. I chose to amortise the costs of the laser over 10 years rather than only 3 but reducing the lifetime of the laser to 3 years increased the cost of each operation by only £22. This demonstrates yet again the greatest cost of FLACS is the cost of the PI rather than the laser itself.

In addition to the above, there are important limitations to mention regarding this hypothetical model. The model assumes that all patients are suitable for a high volume FLACS theatre list. However some patients may not be suited to FLACS or to a high volume service, although the number of contraindications for FLACS are decreasing as experience with the technology improves (Conrad-Hengerer, Hengerer, Joachim, et al., 2014; Dick and Schultz, 2014a; Hatch et al., 2015).

Departmental costs used in this model were obtained from a retrospective review of the financial records at 4 NHS foundation trusts. To ensure that the results were applicable to more than just one hospital with its associated population, 2 teaching hospitals and 2 district general hospitals of varying sizes, with annual numbers of between approximately 1,400 and 5,000 cataract operations were selected for this study. These hospitals serve both urban and rural populations (range approximately 275,000 to 823,000 served by each hospital) with a mixture of demographics (and include hospitals with one of the highest and one of the lowest cataract tariffs) (Department of Health, 2016a).

The costs of consumables were assumed to be equal for FLACS and CPS. In reality, as the FL performs many stages of the procedure, the cost of some consumables may be reduced (vision blue, disposable capsulorrhexis forceps, less likelihood of additional viscoelastic etc.) and some cataracts may no longer require any phacoemulsification (Abell, Kerr, and Vote, 2013b). Our model incorporates the salary of a registrar to operate the laser (Cohen et al., 2015; Hou et al., 2015), yet if FLACS becomes widely adopted within the UK, then technicians may be trained to perform this duty, perhaps at a reduced cost. However, but no money was saved when the salary of a band 6 nurse to operate the laser instead of a doctor was introduced into the financial modelling.

Overall, this model demonstrates that FLACS could only be financially viable if its implementation into the NHS allowed significant improvements in efficiency in the number of cases treated per theatre list and or if the cost of the PI was considerably reduced. Further research is required on the clinical outcomes of FLACS compared with CPS as well as real-world evidence of the effect to surgical efficiency afforded by this technology.

Chapter 4. Risk-adjusted CUSUM analysis of the learning curve of femtosecond laser assisted cataract surgery

4.1. Introduction

The adoption of any new surgical technique or equipment may lead to a temporary increase in complications during the learning curve phase. Increased rates of complications within any learning curve raise ethical questions and highlight the need for mechanisms to reduce complications. Studies on FLACS have specifically investigated the rates of complications within the learning curve (Lubahn et al., 2014; Bali et al., 2012; Abell, Kerr, and Vote, 2013a; Chee et al., 2015; Day, Dhallu, et al., 2016; T. V. Roberts et al., 2013). Bali et al. compared rates of complications within the first 200 cases between 7 surgeons and found that the first 100 cases had significantly greater rates of number of docking attempts, per-operative miosis and a lower rate of free floating capsulotomy (Bali et al., 2012). The same group later published the complication rates of their subsequent 1,300 cases and found statistically significant reductions in complication rates between the original cohort of 200 and subsequent 1,300 surgeries for anterior capsular tears (4% vs 0.31%, p<0.001), posterior capsular tears (3.5% vs 0.31%, p<0.001), and dropped lens fragments (2% vs 0%, p<0.001) (T. V. Roberts et al., 2013). This provides a good demonstration that there are increased risks of intraoperative complications during the learning curve for FLACS but does not provide an indication of the length of learning curve for an individual surgeon.

Day et al. described the rates of intraoperative complications as well as any issues relating to laser docking and delivery for 158 cataract operations over a during the initial 2 months after the arrival of a femtosecond laser in their department (Day, Dhallu, et al., 2016). A total of 32 surgeons, both consultants and non-consultants took part in the learning curve with a median number of only 3 cases per surgeon. However, two surgeons were already experienced at

FLACS, having performed over 200 cases each. The authors report that 2.7% of operations were complicated by vitreous loss all of which were performed by non-consultants. The authors conclude that their transition to FLACS was safe, based on comparing their complication rates and average post-operative visual acuity to national averages (Day, Donachie, et al., 2015).

Chang et al. described the complication rates of the first 177 FLACS cases between 3 surgeons at their institution (J. S. M. Chang et al., 2014). However, 76% of operations were conducted by one surgeon. 5.3% of surgeries were complicated by anterior capsular tear, which the authors state is not statistically significant compared to their conventional phacoemulsification surgery (CPS) cohort. However, this was was higher than the other studies previously discussed. Posterior capsular tear rate was 0.6% and intra-operative miosis occurred in 10%.

The length of the learning curve has as yet not been investigated and suggestions vary within the literature (T. V. Roberts et al., 2013; Day, Burr, et al., 2015). Christy et al. have suggested that 30 cases are needed before consistency in docking time, number of docking attempts, problems encountered during docking, and complications attributable to docking are stabilised (Christy et al., 2017). However, the protocol for the FACT study require a surgeon to have only completed 10 cases before being allowed to perform FLACS in the study (Day, Burr, et al., 2015). Despite the literature previously published on the learning curve of FLACS there is still a need to demonstrate complication rates and difficulties encountered on an individual surgeon basis of those beginning FLACS.

The aim of this study was to evaluate the learning curve of 3 surgeons (one fully accredited with twenty years' experience, one newly accredited consultant and one specialist registrar) at our institution (Guy's & St Thomas' NHS Foundation Trust) after the arrival of a femtosecond laser (LenSx, Alcon Inc, Fort Worth, TX, USA). Results would be analysed using a risk-adjusted cumulative sum method (CUSUM) to estimate the length of the learning curve.

4.2. Methods

This was a retrospective review of FLACS performed by 3 surgeons (HWR, VKW, DOB) following installation of the LenSx femtosecond laser (Alcon Inc), for cataract surgery at St Thomas' Hospital, London, United Kingdom. Prior to this, all 3 surgeons were naïve to FLACS. All surgeons had received training from the manufacturer. All FL treatments were performed by VKW or HWR and all patients gave informed consent for all treatments received. Cases were identified from the LenSx electronic log and were performed over a 12-month period between June 2016 and June 2017. The project was approved by the Research & Development department at St Thomas' Hospital. Retrospective studies of this type do not require research ethics committee permission.

Details of the first 288 consecutive cases performed by the surgeons were evaluated. These patients included 200 cases that were performed as part of a prospective randomized interventional case-controlled comparing FLACS with CPS (Clinicaltrials.gov registration number NCT02825693, Alcon Inc, Fort Worth, TX, USA. Grant number: IIT#17440075). These cases were reviewed for baseline information (age, gender, etc.), pre-operative biometry, for patient comorbidities and for details on intra-operative complications. Exclusion criteria included dense corneal opacities, requirement for general anaesthetic, dilated pupil size <4mm, inability to lie flat or unable to dock with the FL. All cataract operations were performed under local anaesthetic. All were unilateral, and no other additional procedures planned, other than arcuate keratotomies for reduction of corneal astigmatism. Phacoemulsification was completed using an Infiniti Phacoemulsification machine with Ozil torsional handpiece (Alcon Inc). Intra-operative complications were defined as any event that involved unintentional trauma to an ocular structure.

Learning curve defined as cumulative difference between observed occurrence of PCR (0 or 1) and expected (risk adjusted) risks of PCR. Change point would occur where the CUSUM curve peaked. The assumption is that the surgeon would start off worse than expected with a positive cumulative difference (since complication =1 indicates an occurrence and 0 indicates safe performance). Learning curves were analysed by using risk-adjusted CUSUM curves with individual analyses for PCR and for the event of any complication. Binary outcomes (uncomplicated/1 complication, PCR/no PCR) were risk adjusted. Each patient was risk assessed for probability of PCR using a composite risk calculation system (Narendran et al., 2008). Each operation was risk adjusted for any complication occurring by experience of the surgeon (Day, Donachie, et al., 2015).

The learning curves were analysed separately for each surgeon and pooled. As multiple surgeons provided data, the mean values of the expected and observed outcomes for each case order were computed. CUSUM curves were plotted by comparing observed and expected outcome values, with the use of the equation

$$S_i = \mathrm{S}_{(\mathrm{i}-1)} + \left(X_{i(obs)} - X_{i(\exp)}\right)$$

Equation 1. S = cumulative means, i = case order, X = outcome value, obs = observed, exp = expected

4.2.1. Statistics

Raw data analysis was performed by using Microsoft Excel (Microsoft Excel, Microsoft Corp, Redmond, Washington).

To determine the confidence level of an observed change, a change-point analysis was performed. For this purpose, CUSUM curves were bootstrapped by randomly reordering the cases 5,000 times. By comparing the difference between the maximum and minimum S ($S_{max} - S_{min}$ (ΔS)) of the original CUSUM with those obtained from the bootstrapping samples, a confidence level could be determined for the point of change. A confidence level of >95% was deemed as providing strong evidence that a real change had occurred (i.e. 95% of the bootstrapped ΔS were smaller than the actual database).

4.3. Results

288 cases were reviewed. Patient demographics can be seen in Table 4.3-A. Gross rates of complications were calculated (Table 4.3-B).

% Male	51.8%
% 1st Eye	77.8%
% Right Eye	53.2%
Age (years) ± S.D.	69.62 ± 10.94
Axial length (mm)	24.04 ± 1.41
Anterior chamber depth (mm)	3.33 ± 0.37

Table 4.2.1-1 Baseline demographic data of patients included in this study

	SURGEON 1	SURGEON 2	SURGEON 3	OVERALL
NUMBER OF CASES	98	114	76	288
AVERAGE PCR RISK (NARENDRAN, 2008)	1.44%	1.65%	2.39%	1.73%
PCR	0	1	1	2 (0.7%)
VITREOUS LOSS	0	1	0	1 (0.3%)
ANTERIOR CAPSULAR TEARS	3	4	3	10 (3.4%)
IRIS TRAUMA	0	1	1	2 (0.7%)
DESCEMET'S MEMBRANE TEAR	1	0	0	1 (0.3%)

Table 4.2.1-2 Rates of complication per surgeon

4.3.1. Overall rate of complications

CUSUM curves for the occurrence of any complication for each surgeon and as an overall average can be seen in Figure 4.3.1-A, Figure 4.3.1-B, Figure 4.3.1-C and Figure 4.3.1-D. The pooled data demonstrated stable performance after 16 cases however this was not statistically significant (confidence level =1%). The individual data did not show learning curve effects by CUSUM analysis. Surgeon 1's performance was better than average initially but had late complications (Figure 4.3.1-B). Surgeon 2 demonstrated a learning curve effect with stable performance after the 14th case, but this was not statistically significant (confidence level = 1%) (Figure 4.3.1-C). Surgeon 3 did not exhibit a learning effect (Figure 4.3.1-D)

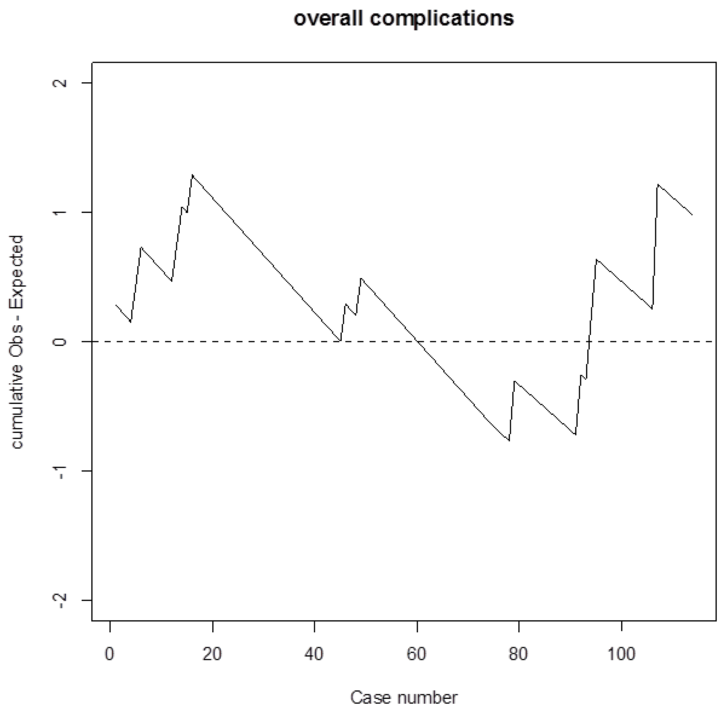


Figure 4.3.1-A CUSUM curve for pooled data on any complication

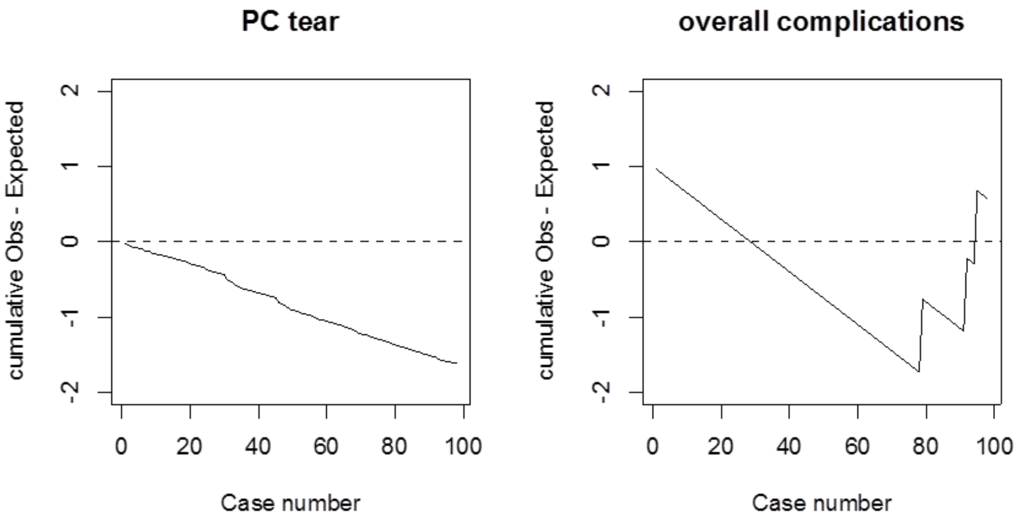


Figure 4.3.1-B CUSUM curve for Surgeon 1 on (A) posterior capsule rupture (B) any complication

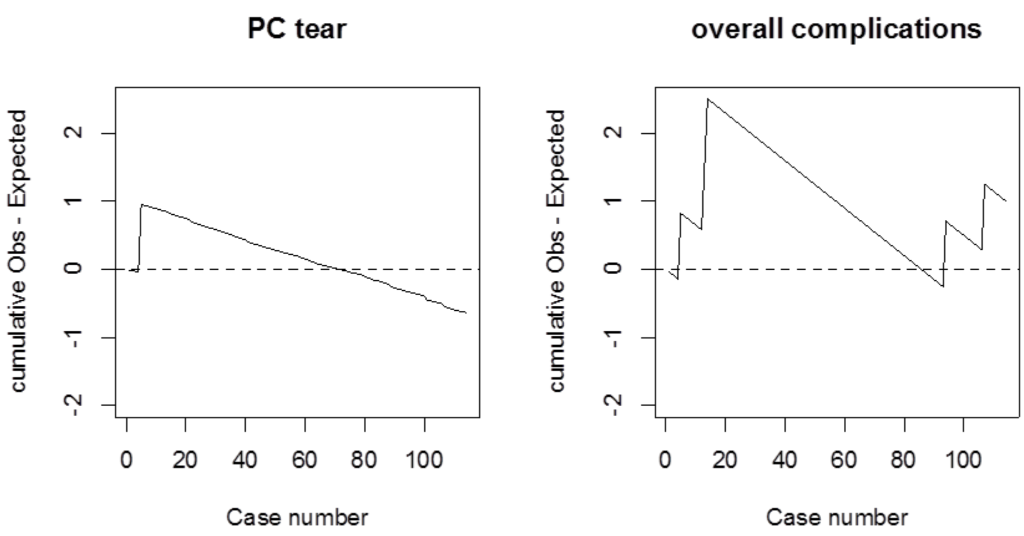


Figure 4.3.1-C CUSUM curve for Surgeon 2 on (A) posterior capsule rupture (B) any complication

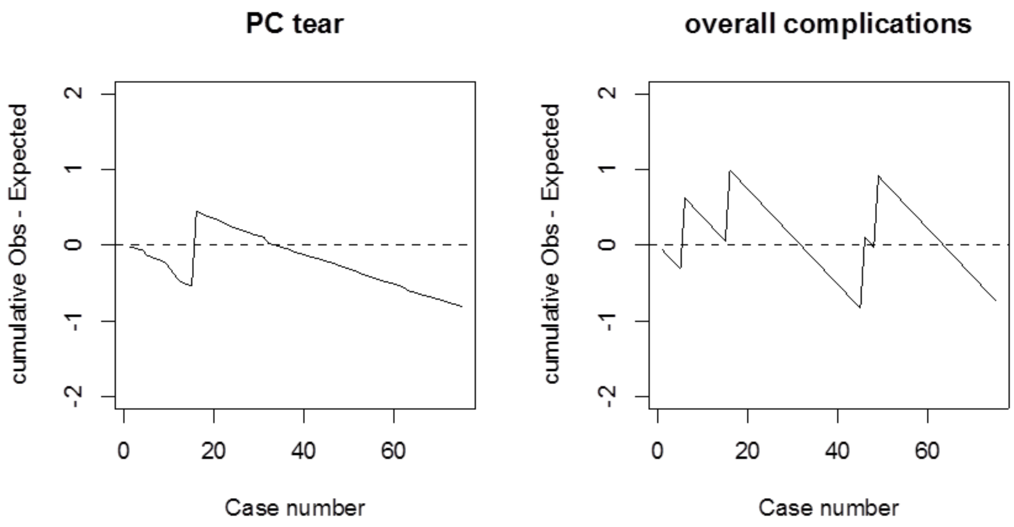


Figure 4.3.1-D CUSUM curve for Surgeon 3 on (A) posterior capsule rupture (B) any complication

4.3.2. Posterior capsular rupture

CUSUM curves for PCR for each surgeon and as an overall average can be seen in Figure 4.3.1-B, Figure 4.3.1-C, Figure 4.3.1-D and Figure 4.3.2-A. There was a strong confidence level (96%) that there was stable performance in terms of PCR after case 16 for the pooled data (Figure 4.3.2-A). Surgeon 1 did not have any cases of PCR (Figure 4.3.1-B), surgeons 2 and 3 exhibited change points at case 5 and 16 respectively (confidence levels = 99%, 98%) (Figure 4.3.1-C and Figure 4.3.1-D).

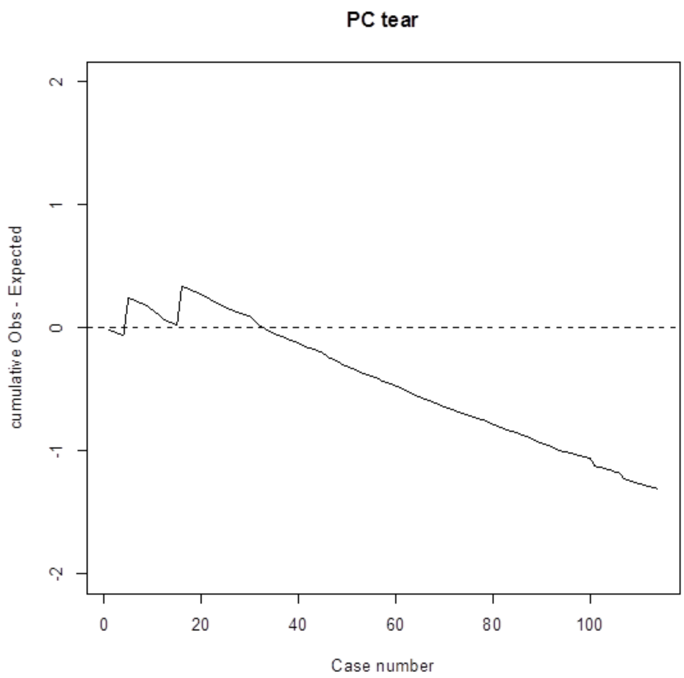


Figure 4.3.2-A CUSUM curve for pooled data on posterior capsule rupture

4.3.3. Laser attributable complications

The overall rate of patients affected by laser attributable complications was 9.6% (n=27) (Table 4.3-A). There was no demonstrable reduction in the incidences of these events over time (Figure 4.3.3-A). 2/27 of these patients sustained intraoperative complications, one of which was felt to be related (anterior capsular tear in a patient who had had an anterior capsular tag) and the other unrelated (iris trauma in a patient who sustained a corneal abrasion).

Complication	**n=**	**%**
incomplete capsulotomy	13	4.5%
post-laser miosis	4	1.4%
AC tag	7	2.4%
laser not completed	2	0.7%
corneal abrasion	2	0.7%
full thickness FS-AK	1	0.3%

Table 4.3.3-1 Rates of laser attributable complications

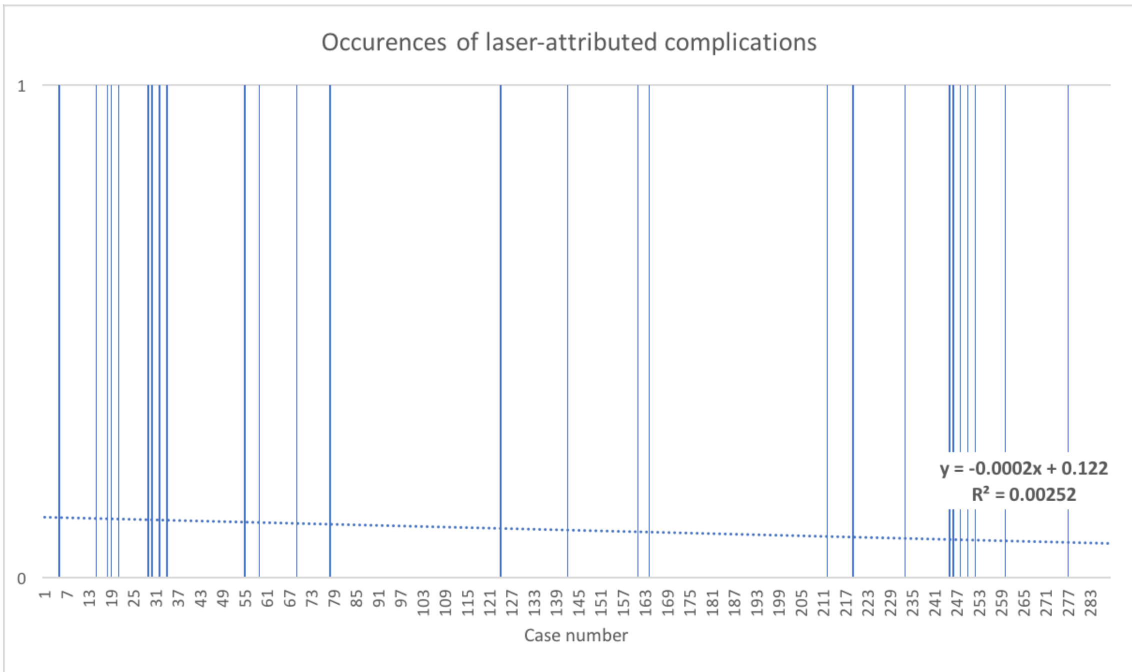


Figure 4.3.3-A Non-risk adjusted CUSUM score for complications attributable to the femtosecond laser during the study

4.4. Discussion

A risk-adjusted cumulative sum method approach was used to estimate the length of the learning curves of 3 cataract surgeons in relation to all intraoperative complications, and specifically posterior capsular ruptures. Determining the length and gradient of the learning curve is important in both consenting patients for FLACS, estimation of surgical risk, determining length of supervised practice, as well as in the planning of future prospective studies of FLACS. The present study found that the length of the learning curve with regards to PCR was 16 cases on average with 96% confidence, but did not find evidence of a learning curve when considering all complications as a whole. Our overall rate of PCR was safe (0.7%) when compared with our expected PCR rate (1.73%) and our rate of anterior capsular tears (3.4%) was consistent with other reports in the literature (J. S. M. Chang et al., 2014). Only one of the anterior capsular tears extended posteriorly, no vitreous was lost and the IOL was placed in the sulcus; in all other cases of anterior capsular tears an IOL was successfully placed in the capsular bag. Figure 4.3.1-A showed that all surgeons continued to have complications which accounted for there being no overall learning curve effect by CUSUM analysis. This could possibly be accounted for that the learning curve was longer than the period of our analysis, but I suggest that it is most likely due to the fact that there does seem to be a slightly increased risk of anterior capsular tears during FLACS compared with CPS and this may be a complication independent of any learning effect (Abell, Davies, et al., 2014).

Over the course of introducing FLACS, several changes to our pre-operative preparation were made, based on evidence from the literature and anecdotal advice from other surgeons experienced at FLACS. These included:

- One drop of topical phenylephrine 10% after FL delivery (T. V. Roberts et al., 2013). N.B. Phenylephrine 10% has been shown to be associated with a significant change in cardiovascular parameters compared to phenylephrine 2.5%, namely an increase in pulse by 4.5beats/min and blood pressure by 15mmHg within the first 10 minutes after administration(Stavert et al., 2015). It should therefore be used with caution in those at risk of cardiovascular events, however no adverse events occurred within our study.

- Two drops of topical pre-operative diclofenac sodium 0.1% w/v (L. Wang et al., 2016; Yeoh, 2014; Diakonis et al., 2017; Hwa Jun et al., 2017)
- Pre-operative mydriasis using Mydriasert (0.28 mg/5.4 mg ophthalmic insert, Thea Laboratories, Clermont-Ferrand, France)
- All surgeons encountered cases with increased difficulty during removal of soft lens matter with irrigation/aspiration (I/A)(Day et al., 2018). One surgeon found that these cases were facilitated by using bimanual rather than coaxial (I/A) (Conrad-Hengerer, Schultz, et al., 2014).

Incorporating these changes resulted in more consistent mydriasis with no further episodes of iris trauma secondary to intraoperative floppy iris syndrome (Diakonis et al., 2017). Other complications included one Descemet's membrane tear which resulted in localized wound-associated post-operative corneal oedema which resolved by 3 months. There were no episodes of dropped lens matter. Of the two cases of PCR, one was felt to be unrelated to the laser treatment. The other was because of early posterior extension of an anterior capsular tear and therefore attributable to the FL treatment.

Following refinement during the learning curve, the three surgeons adopted the same preferred laser settings (Table 4.3.3-B). In summary, this consisted of a sextants chop pattern with a central 2mm cylinder core (Figure 4.3.3-B and Figure 4.3.3-C). This pattern facilitated easy nuclear disassembly and removal via initial phacoaspiration of the central core, allowing the instruments to be inserted towards the posterior pole of the lens with subsequent completion of the 6 cracks. Six was chosen as the preferred number of segments, as removal of quadrants in large lenses may stress the anterior capsulotomy and octants could be too small with a reduced surface profile to present to the tip of the phacoemulsification probe.

LENS METHOD	*CHOP*	*CYLINDER*
DIAMETER (mm)	6	2
LENS ANTERIOR OFFSET (um)	500	500
LENS POSTERIOR OFFSET (um)	800	800
ZONE 1 ENERGY	10	10
ZONE 2 ENERGY	10	10
ZONE 3 ENERGY	10	10

ZONE 4 ENERGY	10	10
ZONE 5 ENERGY	10	10
NUMBER OF CHOPS/CYLINDERS	3	1
SPOT SEPARATION (um)	14	10
LAYER SEPARATION (um)	14	14
CAPSULOTOMY PARAMETERS		
DIAMETER	5	
CAPSULE DELTA UP (um)	250	
CAPSULE DELTA DOWN (um)	250	
ENERGY	6	
SPOT SEPARATION (um)	4	
LAYER SEPARATION (um)	3	
ARCUATE INCISION PARAMETERS		
DIAMETER (mm)	9	
PERCENT POST DEPTH (%)	80	
ENERGY	3	
SIDE CUT ANGLE	90	
SPOT SEPARATION (um)	4	
LAYER SEPARATION (um)	4	
ANTERIOR OVERLAP (um)	50	
NUMBER OF ARCS	2	

Table 4.3.3-2. Our LenSx preferred settings after completion of the learning curve

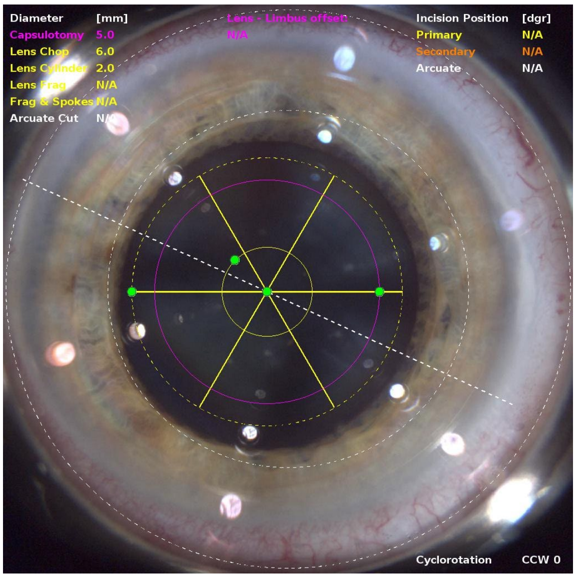


Figure 4.3.3-B LenSx display of 6mm 3 chop pattern with 2mm central cylinder with 5mm capsulotomy (our preferred settings)

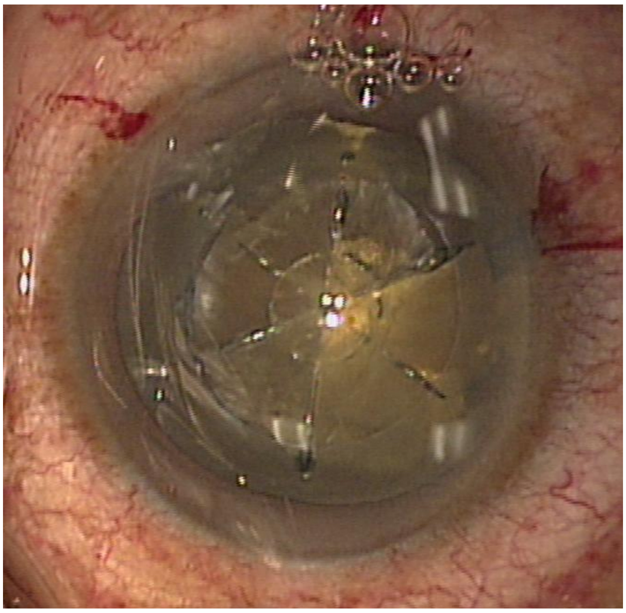


Figure 4.3.3-C Operating microscope photograph of our preferred segmentation pattern

One asset of this study is that the three surgeons had different levels of experience with cataract surgery (one fully accredited with twenty years' experience, one newly accredited consultant and one specialist registrar). Despite these differences the complication rates and learning curves were safe for each surgeon when evaluated individually. Previous studies have evaluated the safety of FLACS for surgeons in training and demonstrated reduced rates of PCR when compared to a cohort of CPS (Pittner and Sullivan, 2017; Brunin et al., 2017).

All surgeons performed their first cases of FLACS within these series. The surgeons had received full training from the manufacturer and were experienced at CPS, but complication rates may have been even lower if structured supervised training by an experienced FLACS surgeon had been implemented. FLACS introduces significant differences to a surgeon's technique for CPS. As there is a demonstrated learning curve effect of FLACS, I suggest this underlines the need for structured supervised training with an experienced FLACS surgeon in addition to full training and accreditation by the manufacturer as well as objective assessment of competency in FLACS. Once surgeons start to perform independently, careful case selection is a key to avoid unnecessary complications as well as continuous audit of results to ensure best possible patient safety.

The important limitations of this study are felt to be two-fold. Using CUSUM for analysis of learning curves is an important and valid method (Grigg et al., 2003). However, CUSUM analysis provides no indication of the time interval between cases or the case mix of the surgeon which may influence results. Furthermore, it does not account for the severity of the complications incurred, with an equal inflection of the learning curve for the most inconsequential and most sight threatening complications.

This study used an established composite risk calculation system based on 55,567 cataract operations to determine estimated risks of PCR in this cohort (Narendran et al., 2008). Our observed rates of PCR were superior to our predicted rate. This may be due a number of factors including the improved awareness of risk factors for PCR and how to mitigate these risks since the original paper was published (e.g. alpha adrenergic antagonists). Alternatively, the relative risks for PCR in CPS may not be as valid for FLACS, for example FLACS has been found to be safe in case series on white cataracts or subluxed lenses(Conrad-Hengerer, Hengerer, Joachim, et al., 2014; Schultz and Dick, 2014; Titiyal et al., 2016; Chee et al., 2017).

In summary this study found that the learning curve for FLACS is relatively short when considering posterior capsular rupture and that overall complication rates are safe when compared with national averages.

Chapter 5. A randomised controlled trial comparing femtosecond laser assisted cataract surgery vs. conventional phacoemulsification surgery

Supplementary Material #3. Roberts, H.W., Wagh, V.K., Sullivan, D.L., Hidzheva, P., Detesan, D.I., Heemraz, B.S., Sparrow, J.M. and O'Brart, D.P., 2019. A randomized controlled trial comparing femtosecond laser–assisted cataract surgery versus conventional phacoemulsification surgery. Journal of Cataract & Refractive Surgery, 45(1), pp.11-20.

5.1. Introduction

The introduction of FL technology to allow the automation of a number of surgical steps within cataract extraction has been claimed to offer potential advantages of reduced complications and better visual outcomes through greater surgical precision and reproducibility (L. Mastropasqua, Toto, Mattei, et al., 2014; Kránitz et al., 2012). However, systems to undertake FL assisted cataract surgery (FLACS) are expensive both to purchase and use. In chapter 3, it was estimated that FLACS adds £167 (approx. 220USD) to each operation within the context of a state-funded healthcare system (H. W. Roberts MSc FRCOphth, Ni, et al., 2017). From a public health perspective, costs may be mitigated by improved safety leading to increased reliability and reduced post-operative need for additional clinical or surgical interventions, and better patient outcomes (Qatarneh et al., 2012).

The aim of the present study was to complete the largest RCT published to date comparing FLACS with CPS with the intention to inform clinical practice and health policy worldwide. As there have been a lack of patient reported outcome measures (PROMs) in previous RCTs, this study aimed to correct this by measuring quality of life with EuroQOL's EQ-5D and patient reported quality of vision with Cat-PROM5 (Sparrow et al., n.d.; 2018).

5.2. Methods

The study design was a prospective randomised interventional case-controlled study at a single University Hospital (Guy's & St Thomas' Hospital NHS Foundation Trust, London, UK) to compare FLACS with CPS (Clinicaltrials.gov registration number NCT02825693). The study was approved by local Research & Development and Cambridge South Research Ethics Committee (reference 16/EE/0180). This study was conducted adhering to the tenets of the Declaration of Helsinki.

Patients were screened, recruited and informed consent obtained from routine cataract clinics by members of the trial team (HWR, VKW) as per the trial protocol (Version 2.0, 18/05/2016). Inclusion and exclusion criteria are listed in Table 5.2-A. Within the enrolment visit, patients had a complete ophthalmological examination. Only one eye per patient was enrolled to the study. Patients were randomised to receive CPS or FLACS in equal proportions using computer generated random number tables (Microsoft Excel, Microsoft Corp, Redmond, Washington) just prior to being offered a date for surgery. Excel Macros were used to perform the randomisation (this was concealed from the allocator) and then lock the allocation with the patient's research information to address allocation bias. All patients' treatments in this study were delivered by the NHS and were free at the point of care. At the follow up visit, if the patient failed to attend, the patient was contacted and offered another appointment within one week. If they failed to attend this, they were considered lost to follow up from the study.

Inclusion Criteria:
Patients must have reduced visual acuity or visual symptoms attributed to the presence of cataract in one or both eyes by the examining ophthalmologist or else must require cataract surgery on clinical grounds other than visual symptoms.
Patients must be willing to attend for follow-up at 3-4 weeks after cataract surgery.
Patients must have sufficient English language for informed consent and completion of the patient reported outcome questionnaires.
Exclusion Criteria:
Children below the age of 18
Already enrolled in another study
Clinical contraindications for FLACS, such as:
Significant corneal opacities
Small pupils (<4mm) following pharmacological dilatation
Patients unable to lie sufficiently flat to be positioned underneath the laser machine.

Table 4.3.3-3. Inclusion and exclusion criteria for enrolment into the study

Data collection for this study occurred at the pre-operative assessment, the day of surgery, and the post-operative visit scheduled at 4 weeks after surgery (Table 5.2-B). Visual acuity and any investigations performed (corneal topography, specular microscopy etc.) were conducted by an optometrist or technician (DS, PH, DD) masked to the participant's treatment arm. Due to the nature of the intervention, neither the surgeon, surgical team nor the participant could be masked to their treatment arm. All clinical technicians and nurses were masked to the intervention received. Visual acuity (unaided, best corrected, and pinhole) was measured with a Snellen chart at 6 meters. This was not ideal for a study of this nature with visual acuity as the primary outcome measure but occurred due to logistical reasons as the department at the time was using Snellen visual acuity, however has since switched to COMPLog (Complog Clinical Vision Measurement Systems Ltd, London, UK) Participants' refractive errors were collected using an RK-501A Autorefractor (Nidek Co. Ltd, Aichi, Japan). Biometry was performed using an IOL master 500 (Carl Zeiss Meditec AG, Switzerland). Corneal topography was performed with Pentacam (Oculus, Germany). Macular Optical Coherence Tomography (OCT) was performed with Spectralis SD-OCT (Heidelberg Engineering, Germany). Endothelial cell count (ECC) was performed with Topcon SP-3000 Specular Microscope (Topcon Medical Systems, Oakland, NJ, USA). Visual comorbidities and risk factors for complications of cataract surgery were recorded prospectively. Risk of posterior capsular rupture (PCR) were calculated for patients using a composite risk calculation system (Narendran et al., 2008). PROMs were collected with the Cat-PROM5 tool and QoL were assessed using the EuroQOL EQ-5D questionnaire. The EuroQuol 5D consists of 2 components: 5 questions about 5 dimensions of health-related quality of life (mobility, self-care, usual activities, pain/discomfort, and anxiety/depression) which are scored as 1, 2, or 3 (1 meaning no problems and 3 meaning extreme problems). The 5 responses are then weighted and combined to create a summary index with values 0-1, where 1 indicates no problems. The visual analogue scale is a continuous scale anchored by best imaginable and worst imaginable health, with values ranging from 0 to 100 (where 100 indicates best possible health). EQ-5D was chosen as it is well recognized by public bodies (such as NICE) for comparative health economic analyses(Tosh et al., 2012). The Cat-PROM5 is a recently developed NIHR funded questionnaire consisting of 5 questions which provide a Rasch calibrated psychometrically robust measure which is highly responsive to cataract surgery (Sparrow et al., n.d.; 2018).

	Baseline	Day of surgery	Post-operative visit 3-4weeks
Baseline demographics	X		
Unaided distance visual acuity (UDVA)	X		X
Corrected distance visual acuity (CDVA)	X		
Pinhole visual acuity (PHVA)	X		X
Intraocular pressure (IOP)	X		X
Risk factors for cataract surgery(Narendran et al., 2008)	X		
Inclusion/Exclusion criteria	X	X	
Refractive error	X		X
Keratometry	X		
Biometry	X		
Corneal topography	X		X
Endothelial cell counts	X		X
Optical coherence tomography of the macula	X		X
EQ-5D-3L	X		X
CAT-PROM5	X		X
Adverse event collection		X	X

Table 4.3.3-4 Schedule for data collection

FLACS treatment was performed using the LenSx Femtosecond laser (Alcon Inc. Fort Worth, Tx, USA). Two surgeons (HWR, VKW) received training and full accreditation on the device in anticipation of this trial and performed at least 30 laser applications each before the trial began. The femtosecond laser was used to perform capsulotomy, lens fragmentation ± astigmatic keratotomies. Where the laser treatment could not be performed for whatever reason (e.g. repeated inability to dock, laser machine fault, etc.) patients underwent surgery in accordance with conventional CPS. FS-AKs (within the FLACS group) or limbal relaxing incisions LRIs (within the CPS group) were offered to any patient with corneal astigmatism greater than 0.9D based on corneal topography. The astigmatic results are presented in chapter 7. All cataract operations were performed under local anaesthetic. All operations were unilateral, and no other additional procedures were planned, other than arcuate keratotomies for the reduction of corneal astigmatism.

The decision was made not to use the CCI function of the FL for several reasons. Two of the three trial surgeons do not place their incisions in clear cornea. The surgeon who did use CCIs did evaluate this function during the learning curve but found that opening the wounds with a blunt instrument took longer than making a manual CCI with a keratome, with no significant clinical advantage gained.

Following FL treatment, the patient was transferred to the operating theatre for the remainder of the cataract extraction. Phacoemulsification was performed using the Infiniti phacoemulsification machine (Alcon Inc.) Patients undergoing CPS were prepared for surgery in the same way as those in the laser arm. Instead of receiving laser pre-treatment, they were brought straight to theatre. All operations were performed by surgeons who had completed at least 30 FLACS procedures (HWR, VKW, DOB).

	FLACS	CPS
Male/female	**100/100**	**82/118**
1st Eye/2nd Eye	**162/38**	**168/32**
Right Eye/Left Eye	**107/93**	**109/91**
Age (years)	**69.9 ± 10.9**	**70.5 ± 9.8**
Pre-operative best corrected distance visual acuity (logMAR)	**0.62 ± 0.49**	**0.54 ± 0.46**
Spherical equivalent refractive error (D)	**-0.17±2.99**	**-0.77 ± 4.88**
Axial length (mm)	**23.88 ± 1.55**	**23.63 ± 1.26**
Anterior chamber depth (mm)	**3.25 ± 0.42**	**3.21 ± 0.44**
Target refraction (D)	**-0.21 ± 0.34**	**-0.22 ± 0.4**
Intraocular pressure (mmHg)	**13.7 ± 4.1**	**13.9 ± 3.6**
Central corneal thickness (µm)	**541 ± 49**	**546 ± 35**
Endothelial Cell Density (cells/mm²)	**2505 ± 313**	**2534 ± 327**
Central foveal thickness (µm)	**199 ± 47**	**189 ± 33**
Average predicted PCR risk(**Narendran et al., 2008)**	**1.63% ± 0.91%**	**1.59% ± 1.29 %**
CAT-PROM5 Calibrated Score	**0.45 ± 2.6**	**0.28 ± 2.31**
EQ-5D-3L Index Score	**0.82 ± 0.19**	**0.80 ± 0.23**
EQ-5D Visual Analogue Scale	**77.84 ± 16.53**	**75.17 ± 18.63**

Table 4.3.3-5 Baseline characteristics for the two treatment arms. (D= Dioptre, LogMAR = logarithm of minimum angle resolution, PCR = Posterior capsule rupture)

5.2.1. Statistics

Baseline characteristics were summarised for each treatment arm (Table 5.2-C). Results were analysed primarily as per intention to treat. Evaluators were masked to the participants' treatment arm. For all evaluations of visual acuity as an outcome, patients with visually significant ocular co-morbidities were excluded prospectively. Snellen visual acuities were converted to LogMAR for analysis(Lange et al., 2008). Continuous data was reported using means and standard deviations if data appear Gaussian. Binary data was reported as frequencies and percentages and evaluated with Fischer's exact test. Student's t-tests were used for parametric data. All statistical tests used a two-sided p value of α=0.05 unless otherwise specified. Intra-operative or post-operative complication were defined as any event that involved unintentional trauma to an ocular structure, requiring additional treatment, or having a negative effect on participants' eyesight. EQ-5D index scores were calculated using the visual analogue score method calibrated for the United Kingdom. Rasch calibrated Cat-PROM5 scores (logits) were calculated from the questionnaire responses in accordance with the developer's instructions(Sparrow et al., n.d.).

Uncorrected distance visual acuity at 4 weeks was designated as the primary outcome with intra- and post-operative complications, refraction, corneal thickness, endothelial cell loss and quality of life outcomes and patient reported quality of vision pre-operatively and at 4 weeks after surgery selected as secondary outcomes. *A priori* calculations for sample size indicated a total sample size of 370 to have an 85% chance of detecting a 0.1 difference in LogMAR visual acuity and assumption of σ=0.32 with α=0.05 and a two-tailed analysis. This sample size was rounded up to 400 to account for the possibility of patients lost to follow up.

5.3. Results

427 patients were recruited to the study between August 2016 and June 2017. 27 patients withdrew from the trial before surgery. 400 eyes of 400 patients received surgery between November 2016 and June 2017 (200 CPS, 200 FLACS). 9 patients failed to attend their follow up appointments (2.3%). 7 participants lost to follow up were in the CPS group compared with 2 in the FLACS group (p=0.17). Only one of the participants lost to follow up had had an untoward clinical event (CPS arm), requiring referral to vitreoretinal colleagues, and withdrew from providing further information to the study team, the remainder had had uneventful clinical courses (Table 5.3-A).

182 (45.5%) of participants were male, 330 (82.5%) of operations were on first eyes, 216/400 (54%) were right eye operations. The average age of patients was 70.2 ± 10.4 years. Average pre-operative best corrected distance LogMAR visual acuity was 0.58 ± 0.47. Patient demographics and full baseline data can be seen in Table 5.3-B. Clinical and self-reported questionnaire measures were similar between the 2 groups. 155/400 operations (39.0%) were on-axis and 314/400 (78.5%) operations were performed with the main incision sited at the corneal limbus and 86/400 (21.5%) with clear corneal incisions. 49/400 (12.3%) of patients were excluded from post-operative visual acuity analysis due to pre-existing visually significant ocular comorbidities (FLACS n=28, CPS n=21). Cases were distributed evenly between the three surgeons and between the two treatment arms (p=0.99) (Table 5.3-C).

	FLACS	CPS
Number of patients	2/200	7/200
Proportion female	1/2	2/7
Proportion 1st Eye	1/2	4/7
Proportion Right Eye	2/2	6/7
*Age (years)***	39 ± 16 (28, 50)	65.6 ± 8.8
*Pre-operative best corrected distance visual acuity (logMAR)***	0.89±0.16 (0.78, 1.00)	1.05 ± 0.9
*Spherical equivalent refractive error (D)***	-2.56±0.80 (-1.13, -4.00)	-0.47 ± 0.58
*Axial length (mm)***	25.19 ± 3.44 (22.8, 27.6)	23.6 ± 0.89
*Anterior chamber depth (mm)***	3.67 ± 0.27 (3.48, 3.86)	3.49 ± 0.27
*Target refraction (D)***	-0.17 ± 0.11 (-0.09, -0.25)	-0.23 ± 0.08
*Intraocular pressure (mmHg)***	15.5 ± 3.5 (13, 18)	14.1 ± 5.3
*Central corneal thickness (μm)***	586 ± 20 (572, 600)	546 ± 25
*Endothelial Cell Density (cells/mm²)***	2485 ± 534 (2107, 2863)	2311 ± 237
Average predicted PCR risk(Narendran et al., 2008)****	1.54% ± 0.20% (1.38%, 1.71%)	2.45% ± 3.8 %
Intraoperative complications	0/2	1/7 (PCR, vitreous loss)

*Table 5.2.1-1 Patient demographics for patients lost to follow up in the two treatment arms. (D= Dioptre, logMAR = logarithm of minimum angle resolution, PCR = Posterior capsule rupture). ** Since there are only 2 items in the FLACS group, the actual values have been provided because of the limited value of a standard deviation.*

	FLACS	CPS	p
Unaided distance visual acuity (logMAR)	**0.15 ± 0.19**	**0.15 ± 0.21**	**1**
Pinhole visual acuity (logMAR))	**0.04 ± 0.12**	**0.04 ± 0.12**	**1**
Change in intraocular pressure (mmHg)	**-1.3 ± 4.5**	**-1.7 ± 3.8**	**0.45**
Cumulative dissipated energy	**9.6 ± 7.0**	**11.1 ± 9.8**	**0.08**
Change in central corneal thickness (µm)	**15 ± 25**	**13 ± 19**	**0.50**
Endothelial Cell loss (%)	**10.2 ± 13.7**	**9.7 ± 13.7**	**0.76**
Change in central foveal thickness (µm)	**6 ± 35**	**9 ± 35**	**0.55**
Mean arithmetic spherical equivalent refractive error from target refraction diopters (D)	**-0.01 ± 0.56**	**0.04 ± 0.58**	**0.39**
Mean absolute spherical equivalent refractive error from target refraction (D)	**0.42 ± 0.40**	**0.40 ± 0.46**	**0.65**
% spherical equivalent refraction within ± 0.5D of intended	**67.3**	**72.3**	**0.32**
% spherical equivalent refraction within ± 1D of intended	**92.9**	**93.7**	**0.84**
Change in Cat-PROM5 Calibrated Score	**-2.44 ± 3.13**	**-2.22 ± 2.89**	**0.49**
Change in EQ-5D-3L Index Score	**0.03 ± 0.17**	**0.03 ± 0.16**	**1**
Change in EQ-5D Visual Analogue Scale	**0.71 ± 13.61**	**4.18 ± 13.91**	**0.02**

Table 5.2.1-2 Post-operative results for the two treatment arms. (D= Dioptre, LogMAR = logarithm of minimum angle resolution, PCR = Posterior capsule rupture)

FL treatment was delivered successfully to 96.5% of cases. Patients receiving FLACS spent, a mean time of 5.9±2.0 min in the laser room. 7 cases (3.5%) were unable to receive FL treatment and received CPS. The reasons were as follows: repeated bubbles in interface/flat cornea (n=1), administrative error (n=1), patient compliance (n=2), and patient's palpebral aperture too narrow (n=3). One of these patients suffered an intra-operative supra-choroidal haemorrhage; the others experienced uncomplicated operations. The average number of docking attempts was 1.3 ± 0.7 per patient. Reasons for failed attempts at docking and details of laser treatments delivered can be seen in Table 5.3-D. Average duration of surgical time was 11.7min ± 3.5 for FLACS and 14.7 ± 6.8 for CPS.

Totals	**Surgeon 1**	**Surgeon 2**	**Surgeon 3**	**Total**
CPS	**68**	**87**	**45**	200
FLACS	**69**	**86**	**45**	200
Total	137	173	90	400
			Chi-squared	p=0.99

Table 5.2.1-3 Spread of operations between the three surgeons on the trial

Reason for failed docking attempt	n=	%
Facial anatomy	17	26.6
Bubbles within the interface	19	29.7
Poor docking	2	3.1
Patient compliance/fixation	11	17.2
Software crashing	1	1.6
Narrow palpebral aperture	7	10.9
Patient interface oriented incorrectly	1	1.6
Patient required repositioning	1	1.6
Unrecorded	5	7.8
Total	64	
Complication relating to laser delivery	**n=**	**%**
Anterior capsular tags	3	1.5
Failure to dock	7	3.5
Corneal abrasion	2	1
Incomplete capsulotomy	9	4.5
Total	**21**	**10.5**
Laser procedures performed	**n=**	**%**
Corneal incisions	**0**	**0**
Capsulotomy	**193**	**96.5**
Lens fragmentation	**193**	**96.5**
Arcuate keratotomies	**53**	**26.5**

Table 5.2.1-4 (A). Reasons for failed individual attempts at docking with the patient interface of the femtosecond laser. (B). Complications relating to femtosecond laser delivery. (C). Details of laser procedures performed. N.B. 25.5% (n=51) of the conventional phacoemulsification surgery arm received manual limbal relaxing incisions.

UDVA (LogMAR) after CPS was 0.15±0.21 and 0.15±0.19 after FLACS (p=1), and PHVA was 0.04±0.12 and 0.04±0.12 respectively (p=1) (Figure 5.2.1-A, Figure 5.2.1-B, Figure 5.2.1-C, Figure 5.2.1-D). Increase in CCT was 13µm±19 after CPS and 15µm±25 after FLACS(p=0.5). ECL was 9.7%±13.7 after CPS and 10.2%±13.7 after FLACS (p=0.76). Refractive mean spherical equivalent error was -0.14±0.60D after CPS and -0.12±0.60D for FLACS (p=0.74) (Figure 5.2.1-E, Figure 5.2.1-F, Figure 5.2.1-G, Figure 5.2.1-H). Change in central foveal thickness (CFT) was 9µm±35 after CPS and 6µm±35 after FLACS (p=0.55) (Table 5.3-B). Cat-PROM5 demonstrated a substantial shift between pre- to postoperative completions, signalling a significant self-reported reduction in visual difficulty following surgery which was similar in the 2 intervention groups.

The EQ5D summary index similarly reflected an improved score which was similar in the 2 groups. The EQ5D visual analogue score was however unchanged in the FLACS group but increased in the CPS group (Table 5.3-B). There were no differences in total rates of intra-operative or post-operative complications (Table 5.3-E, Table 5.3-F). There was a significant difference in the rate of PCR with a higher rate occurring in the CPS group (p=0.03).

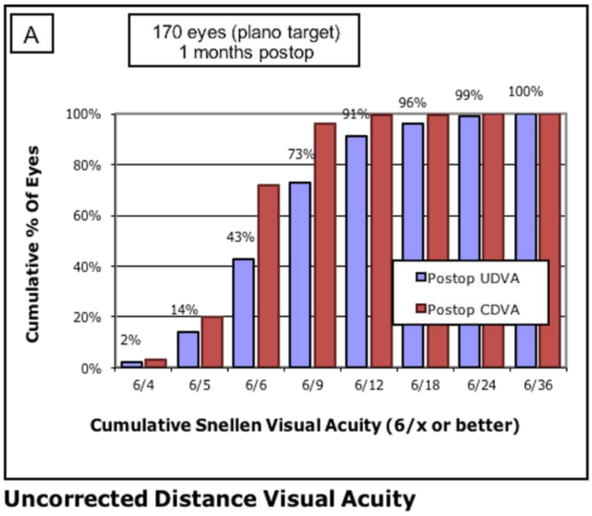


Figure 5.2.1-A Unaided and corrected distance visual acuity at one month after FLACS

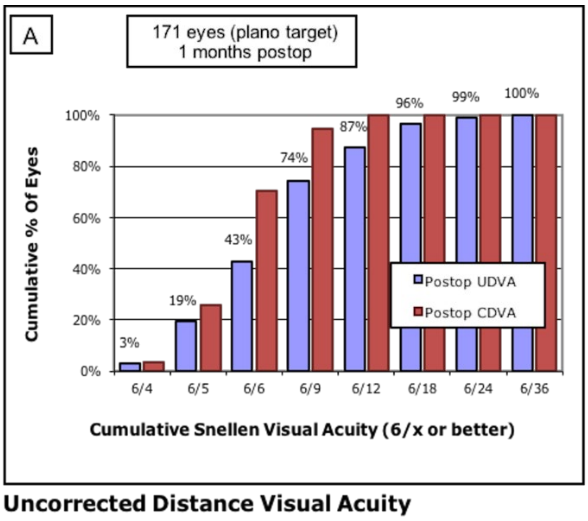


Figure 5.2.1-B Unaided and corrected distance visual acuity at one month after CPS

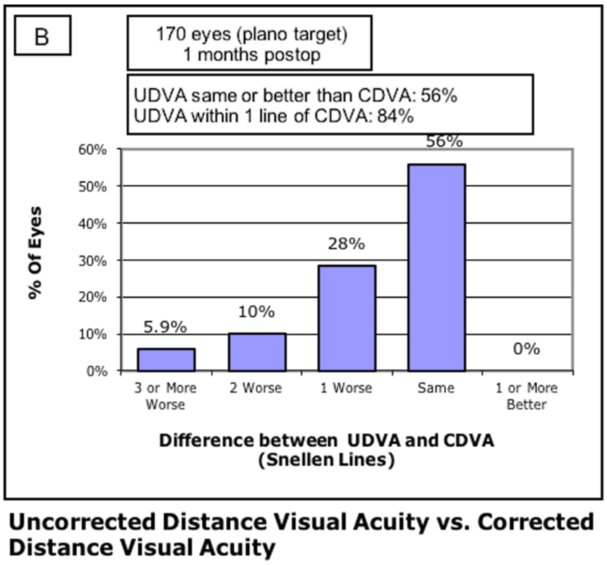


Figure 5.2.1-C Difference between unaided and corrected distance visual acuity at one month after FLACS

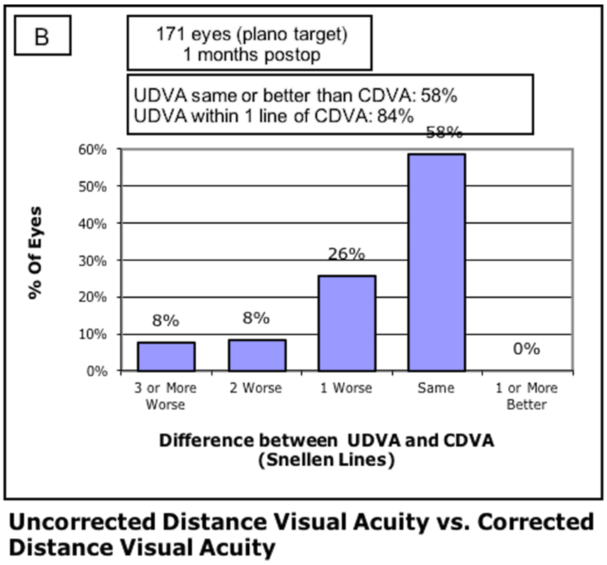


Figure 5.2.1-D Unaided and corrected distance visual acuity at one month after CPS

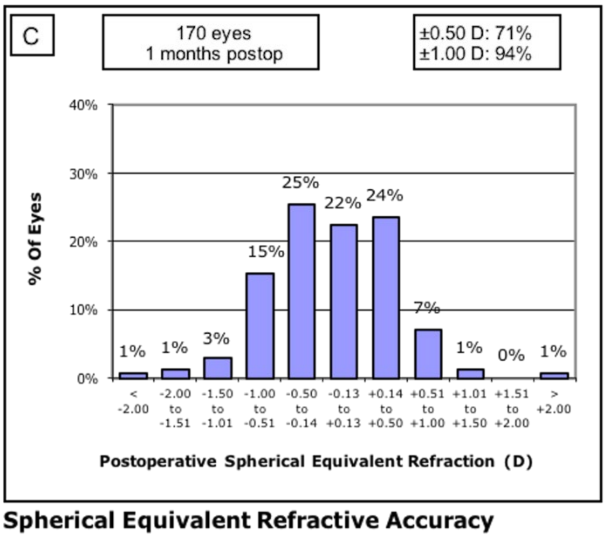


Figure 5.2.1-E Spherical equivalent refractive accuracy one month after FLACS

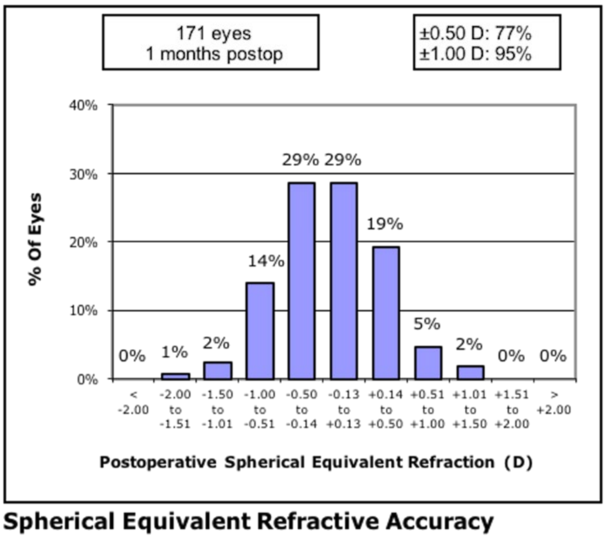


Figure 5.2.1-F Spherical equivalent refractive accuracy one month after CPS

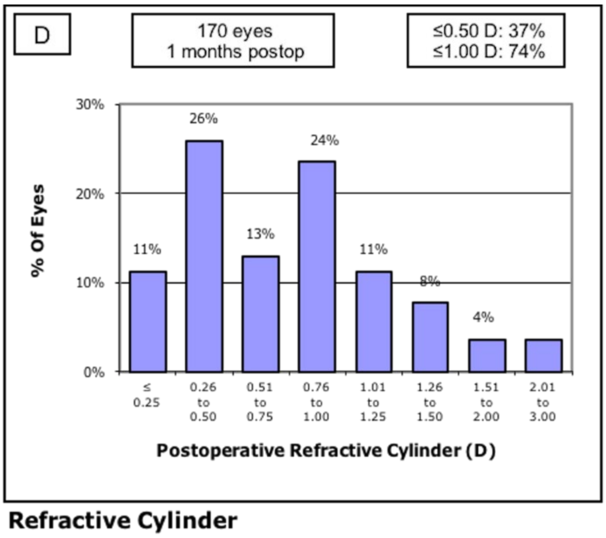
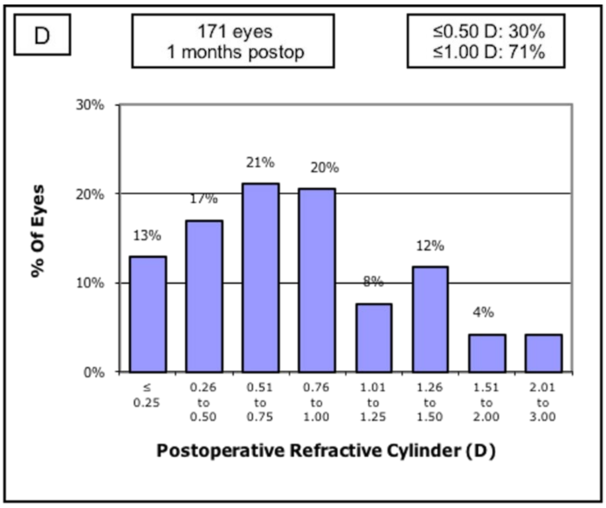


Figure 5.2.1-G Postoperative refractive cylinder one month after FLACS



Refractive Cylinder

Figure 5.2.1-H Postoperative refractive cylinder one month after CPS

	FLACS	%	CPS	%	p
Anterior Capsular tear	6	3	3	1.5	0.50
Descemet's Membrane tear	2	1	0	0	0.50
Intraoperative Floppy Iris Syndrome/Iris trauma	3	1.5	8	4	0.22
Residual Soft Lens Matter	1	0.5	0	0	1.0
Intraocular Lens exchange	1	0.5	0	0	1.0
*Suprachoroidal haemorrhage**	1	0.5	0	0	1.0
Posterior Capsular tear	0	0	6	3	0.03
Vitreous loss	0	0	5	2.5	0.06
Dropped lens fragments	0	0	3	1.5	0.25
Zonulodialysis	0	0	1	0.5	1.0
Total number of cases with intra operative complications	14	7	17	8.5	0.71

*Table 5.2.1-5 Intraoperative complications (*this patient had been randomised to FLACS but received CPS).*

	FLACS	%	CPS	%	P=
Corneal oedema	4	2	2	1	0.69
Return to theatre day 1 for suspected vitreous in Anterior Chamber	0	0	1	0.5	1.0
Clinically significant macular oedema	4	2	3	1.5	1.0
*Prolonged anterior uveitis**	2	1	0	0	0.50
Steroid response/Post-operative raised intraocular pressure	2	1	0	0	0.5
Return to theatre for residual soft lens matter in bag	1	0.5	0	0	1.0
Suture abscess	0	0	1	0.5	1.0
Hypotony	0	0	1	0.5	1.0
Suprachoroidal haemorrhage	0	0	1	0.5	1.0
Total number of cases with post-operative complications	11	6.5	5	2.5	0.20

*Table 5.2.1-6 Postoperative complications (*Both patients had been randomised to FLACS but one had received CPS).*

5.4. Discussion

This RCT is larger than any yet published comparing the safety and effectiveness of FLACS vs CPS including 400 eyes of 400 patients. All surgeries were performed by 3 surgeons at a single centre who had previously completed their FLACS learning curve having completed at least 30 cases. Patients were reviewed at 4 weeks post-operatively to perform clinical examination, assess for complications and gather post-operative data.

Overall, these results point overwhelmingly to an absence of clinical differences between FLACS and CPS (except for PCR and EQ-5D VAS), despite this study including a greater number of patients than any RCT preceding it. In many aspects, our findings are congruous with the available evidence and on occasion are in contrast with conventional understanding.

Previously reported gains in visual acuity for FLACS tended to be early (one week after surgery) or late (at 6 months) but equivalence between 1 – 3 months (Xiaoyun Chen et al., 2015; Day, Gore, et al., 2015). This current study found no difference in the post-operative visual acuity between the two groups at one month (Figure 5.2.1-A, Figure 5.2.1-B, Table 5.3-B). It is conceivable that FLACS has superiority in the early phase due to reduced ultrasound energy and reduced corneal oedema resulting in faster visual rehabilitation, followed by equivalence in the interim, with any late differences perhaps due to differences in late lens decentration or posterior capsular opacification (Okada et al., 2014; Kovacs et al., 2014; Yu et al., 2015; Tran et al., 2016). This study showed found no differences in CCT, ECL or rates of corneal oedema at one month after surgery.

Measurement of post-operative intraocular pressure occurred after the window one usually expects to identify post-operative pressure spikes. In the two patients seen with raised IOP post op, both were due to a steroid response. Indeed, no differences were found in the IOP change between the two groups. Furthermore, no adverse events were recorded of patients presenting in the early post-operative phase with the sequelae of raised IOP.

This is the first large scale randomised controlled trial to evaluate rates of clinically significant macular oedema (CSMO) between FLACS and CPS. Our rates of CSMO were equivalent between the two groups (FLACS 2%, CPS 1.5%) and there was no overall difference in the mean change in CFT. This is in keeping with previous reports (Conrad-Hengerer, Hengerer, Juburi, et al., 2014; Levitz et al., 2015). Of the 7 cases of CSMO in this study, risk factors were prospectively identified for 5 cases (previous macula off retinal detachment = 1, previous epiretinal membrane peel = 1, previous central retinal vein occlusion = 1, epiretinal membrane = 2). A recently published large RCT (PREMED) demonstrated the efficacy of combined bromfenac and dexamethasone in the prophylaxis of CSMO in comparison with either agent in isolation(Wielders et al., 2018). This was not published in time to influence our management and hence patients routinely received only dexamethasone post-operatively. However our rates of CSMO (1.75%) were lower than expected based on the incidence in the PREMED study of 5.1% in patients with no comorbidities. A retrospective case-control series of cataract surgery in patients with neovascular age related macular degeneration (nAMD) showed no difference in post-operative visual acuity, macular thickness or number of intravitreal injections between 17 eyes treated with FLACS compared with 123 eyes treated with CPS (Enz et al., 2018).

This study found a statistically significant increase in the rate of PCR in the CPS group. This is an important finding due to the associated risks of further complications in the post-operative phase associated with increased morbidity and cost (Qatarneh et al., 2012; Day, Donachie, et al., 2015). The Cochrane review of published RCTs reported an overall rate of PCR in 0/529 cumulative FLACS cases compared with (1/547, 0.1%) for CPS (Day, Gore, et al., 2015). It might be considered that the rates of PCR in both these groups to be lower than expected; perhaps reflecting patient selection for the studies or the expertise of the surgeons or both. The EUREQUO case control study compared 2814 FLACS cases with 4987 CPS and found no significant difference in the PCR rates of 0.4% and 0.7% (p=0.79) respectively(Manning et al., 2016). The two other largest studies of note included a case series of over 7000 operations in the public sector in the US (which found a greater rate of vitreous loss in the CPS group) (Scott et al., 2016) and a case-control study of over 4000 patients which found no significant difference in PCR rates (Abell et al., 2015). Our study was performed in the public sector in a hospital based within an inner-city area of London with the accompanying demographics and high rates of co-morbidities. Of the patients sustaining PCR in our cohort the mean composite risk calculation score was 2.04% (Range 0.84% - 3.13%) (Narendran et al., 2008), suggesting that although on the high side, the 3% rate in the CPS arm of our study was at least in part a reflection of the surgical case complexity in our patient cohort. The lower rate in the FLACS group could imply that segment removal is made easier by automated nuclear fragmentation.

It is worth noting that the difference in PCR rates was only just statistically significant. One more PCR in the FLACS group or one less in the CPS group would have rendered this result not statistically significant (and the risk of type 2 error is increased when analysing outcomes with smaller numbers). All but one of the PCRs in the CPS group occurred during the phacoemulsification /fragment removal stage. The nuclear fragmentation patterns of the FL may produce more regular nuclear segments after cracking which may assist the surgeon by ensuring a more reproducible stage 2. It was possible to compare observed rates of PCR with expected rates as this study prospectively risk stratified patients according to a composite risk calculation system (Narendran et al., 2008; Day, Donachie, et al., 2015).

Self-reported visual difficulty and PROMs results were interesting. The Cat-PROM5 scores overall shifted significantly towards less visual difficulty with similar reductions in each group. The EQ5D scores likewise shifted towards better quality of life postoperatively, with similar improvements in each group. There was a significant increase in the EQ-5D visual analogue score after CPS compared to FLACS (p=0.02), however in the absence of a plausible clinical explanation or safety issue, and as there were no differences in the EQ-5D-3L Index Score (p=1.0) or Cat-PROM5 Calibrated Score (p=0.49). In view of such a finding this may be the result of a type 1 statistical error. Furthermore the EQ5D visual analogue score is known to correlate poorly with the impact of cataract surgery (Ang et al., 2013). One limitation was that both first and second eye operations were pooled for the self-reported outcomes. Both CPS and FLACS groups had the same proportion of first/second eye surgeries, however binocular function will be affected by the visual status of the fellow eye, whether cataractous or with a clear lens. One advantage of Cat-PROM5 as a PROM is that it aims to ascertain the effect of vision of the eye in question on overall binocular function(Sparrow et al., n.d.).

Our anterior capsular tear rate was greater in the FLACS group (3% vs 1.5%) but this was not statistically significant. Anterior capsular tear rates in other RCTs were, again, low. However Abell et al. found increased risk of anterior capsular tears in FLACS compared with CPS, as discussed in chapter 1 reflecting the 'postage-stamp edge' microanatomy of the capsulotomy rim (Abell et al., 2015; Yu et al., 2015; Conrad-Hengerer et al., 2013; Reddy et al., 2013; Takagi et al., 2017). In our experience the FL anterior capsulotomy is more likely to tear than a manual CCC, which resulted in each surgeon adapting their surgical technique during each of our learning curves i.e. not to overly stretch the capsulotomy by removing large and dense fragments. This is in turn facilitated by predictable capsulotomy and lens fragmentation sizes created by the FL.

In contrast with other studies, this study did not show that FLACS resulted in more predictable refractive outcomes than CPS (Filkorn et al., 2012; L. Mastropasqua, Toto, Mattei, et al., 2014; Yu et al., 2015). Our overall median absolute error (0.32D for FLACS and 0.29D for CPS) and proportions within ±0.5D, ±1.0D were similar between both groups and in keeping with other studies in the literature (Figure 5.2.1-E, Figure 5.2.1-F). However, in a subgroup analysis of this same study, better outcomes with FS-AKs compared with manual LRIs were demonstrated (Chapter 7).

One more surprising result is that this study did not realize the reduction in phacoemulsification energy (CDE) previously reported with FLACS (9.6 ± 7.0) compared with CPS (11.1 ± 9.8, p=0.08). There was a non-significant result. However our surgeon preference for segmentation of the cataract rather than fragmentation into cubes may have been a factor. Two studies have demonstrated reduced ultrasound energy in FLACS, but either using a grid pattern, or segmentation with multiple concentric cylinders (Abell, Kerr, and Vote, 2013b; Yesilirmak et al., 2017). Less CDE was used in a group of 34 patients treated with a 'complete' fragmentation pattern compared with 37 patients treated with a 'quadrant' pattern (Huseynova et al., 2015). Shajari et al. recently published their findings that CDE was reduced in grid pattern compared with the segmentation pattern which was our favoured technique (Shajari et al., 2017). It follows therefore, that grid pattern softens the nucleus and permits more phacoaspiration, reducing CDE, in comparison with segmentation pattern which requires a nuclear disassembly technique resembling divide-and-conquer.

The limitations of this study include that many clinical outcomes were evaluated leading to an increased risk of type 1 statistical errors. Furthermore, RCTs are often underpowered for safety and complications in cataract surgery are fortunately rare (making it harder to meaningfully evaluate). However, as this is the largest RCT completed to date evaluating complication rates it clearly adds important information to the current literature, including being incorporated in future meta-analyses.

5.5. Conclusion

This large RCT compares the clinical outcomes of FLACS and CPS and confirms, in the majority, the non-significant differences between these two treatment modalities in terms of visual, refractive and a range of other clinical and patient reported outcomes, while suggesting a possibly higher rate of posterior capsular tears following conventional phacoemulsification.

Chapter 6. Evaluation of a hub-and-spoke model for the delivery of femtosecond laser assisted cataract surgery within the context of a large randomized controlled trial

Supplementary Material #4. Roberts, H., Wagh, V. K., Mullens, I. J. M., Borsci, S., Ni, M. Z., & O'Brart, D. P. S. (2018). Evaluation of a hub-and-spoke model for the delivery of femtosecond laser-assisted cataract surgery within the context of a large randomised controlled trial. British Journal of Ophthalmology, bjophthalmol–2017–311319–9. http://doi.org/10.1136/bjophthalmol-2017-311319

6.1. Introduction

Until more evidence is available it is not possible to currently support the widespread introduction of FLACS within public healthcare organisations such as the NHS. This is especially pertinent as by the very nature of its complex technology, FLACS has significant associated financial costs, including initial purchase costs of the laser itself, servicing, depreciation and the individual PI (Chapter 3). These costs seriously question its financial viability, especially in healthcare systems funded by the state.

Studies investigating productivity with FLACS report increased total surgical time and therefore reduced patient turnover and productivity (Abell and Vote, 2014; Bali et al., 2012; Lubahn et al., 2014). One common factor in these studies is that the operating surgeon is typically performing both the FL treatment as well as the subsequent lens extraction within the operating room (OR). There is therefore a transfer time between the FL and the theatre table. This reduction in productivity, is highly important within the public health sector, where high volume surgical models are necessary to meet the both the increasing numbers of patients requiring cataract surgery and economic limitations. It is of note that, the current published literature on the economics of FLACS mainly originates from healthcare systems within the private sector, where supplementary costs of advanced technologies may to a certain extend be passed onto the patient in the form of a co-payment system(Abell and Vote, 2014). However, even in such healthcare models, the literature described FLACS as a longer procedure than

CPS and advocates that FLACS at this time is not cost-effective (Abell and Vote, 2014).

Despite these considerations, FLACS does offer the promise to automate several the component parts of cataract surgery so that they do not need to be undertaken by an appropriately trained ophthalmic surgeon within the OR. Surgical steps such as corneal incisions, arcuate keratotomies, capsulotomies and nuclear lens division can be undertaken with FL by a doctor in training or suitably accredited and trained nurse/technician in a clean room. This has the potential to reduce the amount of time each individual patient spends in the OR with the ophthalmic surgeon. As a result, the efficiency of cataract surgery might be improved by increasing the number of surgical cases undertaken in a given time. This potential efficiency is increased if a hub and spoke model is utilised, with a single FL treating and then feeding patients into several ORs for completion of surgery. Potentially, if the number of cases per theatre session can be increased sufficiently then the additional costs associated with FL technology might be offset. In chapter 3, this possibility was explored using a hypothetical model based on real world financial data (H. W. Roberts MSc FRCOphth, Ni, et al., 2017). It was reported that, in order to break even, there would need to be, for example, a 43% increase in the number of operations performed per theatre list accompanied by a need to discount the cost of the PIs by at least 52% by the manufacturers.

As yet, there are no publications looking at the efficacy, safety and additionally the economics of FLACS compared to CPS, within a ‘hub-and-spoke’ model, as described above, in a real world public health sector setting, where both trainee and fully accredited surgeons undertake surgery, with all the constraints that can be associated with the Public Health Sector, such as limited financial resources, OR space and resistance to change in formalized working practices In order to investigate some of these issues, as part of the RCT comparing FLACS with CPS, we delivered our FLACS service using a hub-and-spoke model. Surgeries were performed by 3 cataract surgeons of differing levels of experience (one fully accredited with twenty years’ experience, one newly accredited and one specialist registrar). Two hundred and ninety-nine of the 400 cases were performed on designated high-volume theatre lists, whereby a hub-and-spoke

FLACS model (with one femtosecond laser and two ORs) was compared to independent CPS theatre lists. Details of operative timings and OR utilisation within these lists were recorded. The aims were to provide the best quality evidence to date on whether FLACS can improve productivity in cataract surgery in the public health sector while maintaining safety and efficacy and what models of FLACS delivery might offset its associated addition costs.

6.2. Methods

6.2.1. Randomised Controlled Trial

This analysis of relative productivity of FLACS delivered by hub-and-spoke model vs CPS was performed as a secondary outcome of a prospective randomised interventional case-controlled study at a single University Hospital (Guy's & St Thomas' Hospital NHS Foundation Trust, London, UK) to compare the clinical outcomes of FLACS with CPS (Clinicaltrials.gov registration number NCT02825693). The study was approved by local Research & Development and Cambridge South Research Ethics Committee (reference 16/EE/0180). This study adhered to the tenets of the declaration of Helsinki.

Methods of the study are described in more detail in Chapter 5.2.

6.2.2. Cataract Surgery Delivery Models

6.2.3. General Model, Staff-duties and Patient Flow

Cataract operations were performed during 4-hour theatre sessions, either in the morning or afternoon. Patients for cataract surgery were admitted on a staggered arrival basis to an ophthalmic day care unit (ODCU) which staffed by a receptionist and a mixture of ophthalmic technicians (OTs) and ophthalmic nurses (ONs) (Table 6.3-C).

After electronic registration by the receptionist, the patients were prepared for the OR by the ON/OTs. This included a series of medical observations, such as blood pressure and blood sugar (if diabetic), and administration of mydriatic therapy. Mydriatic therapy used in this study included a Mydriasert implant (Thea Laboratories, Clermont-Ferrand, France) and two drops of topical diclofenac sodium 0.1% to reduce the risk of intraoperative miosis (L. Wang et al., 2016; Schultz et al., 2013). The ward ON/OTs brought and collected the patients to and from the OR, which were adjacent to the ODCU, after being telephoned by one of the OR nurses (TNs). After surgery was completed the ON/OTs performed further medical observations, gave advice about aftercare, dispensed medication, discharged the patients and arranged follow-up.

Patients were treated on either all-FLACS or all-CPS theatre lists. All cataract operations were performed under local anaesthetic. All were unilateral, and no other additional procedures planned, other than arcuate keratotomies for reduction of corneal astigmatism.

The duties of the ophthalmologist inside the OR included: helping positioning the patient on the operating table, the scribing of patient details onto the whiteboard, the removing of the Mydriasert implant, the marking of the forehead above the eye for cataract surgery prior to the WHO checklist(The World Health Organization, 2009), scrubbing and gowning, leading the WHO checklist, preparation and draping of the eye for surgery, operating, writing the operation notes, and scanning the paper WHO checklist into the hospital's electronic patient record software.

6.2.4. FLACS Hub and Spoke Delivery Model

FLACS theatre lists were run as a hub-and-spoke model (Figure 3.2.2-A). A LenSx femtosecond laser (Alcon Inc, Fort Worth, Tx, USA) was installed in the anaesthetic room of one of the ORs, hereafter referred to as the laser suite (LS), and was used to feed patients into two adjacent ophthalmic ORs which were running in parallel. The FL was operated by an ophthalmologist (HR, VW). The model required an additional OT who supervised patients waiting in the corridor outside the LS (Table 6.3-C). There was a maximum of 4 patients seated in the theatre corridor at any one time (2 patients waiting for laser treatment, 2 patients waiting to enter OR). In the FLACS model, the ophthalmologist performing the FL laser treatment was responsible for marking the patients' eyes before laser, delivering laser treatment, removing the Mydriasert implant, and instilling additional topical phenylephrine 10%. Performing laser treatment included preparing the patient interface, entering patient details into the FL, selecting the planned treatment profile, positioning the patient on the laser bed, instilling topical anaesthetic in to the operative eye, inserting the lid speculum, docking the patient interface to the eye, performing OCT of the anterior segment, choosing the treatment parameters, and delivering the laser treatment. If completion of FL treatment was not possible for any reason, this and the reason why was recorded, and the patient proceeded to the OR for CPS.

The number of patients booked to each 4-hour theatre list were decided in advance of each theatre list. The intention was to attempt to always maximize the number of patients treated during the allotted theatre time with reference to the levels of nursing and para-medical staffing. Initial targets were chosen based on existing experience of CPS and FLACS at our institution and titrated as the trial progressed, according to whether theatre lists were finishing early or over-running.

6.2.5. Operating Room Timings

Two hundred and ninety-nine of the 400 cases were performed on designated high-volume theatre lists, whereby patients were randomized to either hub-and-spoke FLACS model (with one FL and two ORs) or CPS only theatre lists. Various timings of OR utilisation was undertaken by a TN and included the time taken for the patient to enter the OR, duration of cataract surgery, time taken for the patient to exit the OR after completion of surgery, the total individual patient time in the OR, the time the OR was empty between patients, over and under-runs of allotted OR time, etc

Timings of patient entry to the OR, start of operation, end of operation and patient exit from the OR were recorded contemporaneously by TNs using the existing theatre management software (Galaxy Theatre Management System, iSOFT, DXC Technology, Virginia, US). Accuracy of timings was ensured by a trained observer (IJMM). Timings of patient entry and exit from the LS were recorded by the ophthalmologist performing the laser treatment. Start of operation and end of operation were defined as application of antiseptic solution to the eye and skin, and removal of eyelid speculum. Due to the nature of the surgery, it was not possible to mask any of the surgical team to the treatment arm.

6.2.6. Economic Model

The results from this were used as inputs for a hypothetical economic model, reported in a previous publication, to determine an estimation of the costs of cataract surgery (Chapter 3) (H. W. Roberts MSc FRCOphth, Ni, et al., 2017). This financial model has been described in greater detail in the previous chapter but was based on averaged costs/values from 4 different NHS foundation trusts and 4 femtosecond laser manufacturers. This model was used to provide an estimation of the difference in cost per case of running a FLACS service as compared with a traditional cataract service. Furthermore, if the results supported that a hub and spoke model could be run with more than two ORs, these iterations were also tested using the model.

6.2.7. Statistics

For the purposes of this study, the first two CPS and FLACS theatre lists each were excluded from analysis as they were scheduled with reduced patient numbers to allow theatre staff to familiarize with the models. The final four theatre sessions of the study were run as mixed lists to facilitate the scheduling of the remaining research participants and to avoid underutilised theatre sessions. These final mixed lists were also excluded from analysis.

The primary outcome as per the study protocol were the relative costs of FLACS and CPS. However, considering inherent difficulties in accurate recordings of costs within a large tertiary ophthalmology service, it was determined that this would be replaced with the number of cases on FLACS and CPS lists and the duration of the operations. This current study of 299 patients had a power of 99% to detect an effect size (d) of 0.5 for the numbers of participants included in this analysis with regards to duration of surgery with α=0.05 and a two tailed analysis.

Baseline characteristics were summarised for each treatment arm. Results were analysed primarily as per intention to treat. Continuous data was reported using means and standard deviations if data appear Gaussian, or medians and inter-quartile ranges if not. Binary data was reported as frequencies and percentages and evaluated with Fischer's exact test. Student's t-tests were used for parametric data and the Mann Whitney U test for non-parametric. All statistical tests used a two-sided p value of α=0.05 unless otherwise specified. Intra-operative complications were defined as any event that involved unintentional trauma to an ocular structure, requiring additional treatment, or having a negative effect on participants' eyesight.

6.3. Results

A total of 427 patients (427 eyes) were recruited for the study and randomized to receive FLACS or CPS. Twenty-seven were excluded or withdrew in advance of surgery. For this study comparing FLACS in a hub and spoke model with dual CPS theatre lists 299 of 400 operations were included for analysis. Excluded patients included 57 patients who had had surgery on the first 2 of each theatre sessions for FLACS/CPS and 44 patients treated on mixed (CPS and FLACS) theatre lists. There were no significant differences between patients included and excluded for this analysis other than those excluded were on average 3 years older (p=0.01) and had shallower anterior chambers by 0.17mm (p<0.01) (Table 6.3-A). Of the 299 eyes included in this analysis, 134 patients had received FLACS, and 165 patients underwent CPS. Baseline demographics for the FLACS and CPS groups are seen in Table 6.3-B. The only significant difference at baseline was the FLACS group had a longer axial length by 0.39mm (p=0.02). 5 patients due to receive FLACS were treated with CPS due to the following reasons: palpebral aperture too narrow for patient interface (n=3, 2.2%), patient lack of compliance (n=1, 0.7%), administrative error (n=1, 0.7%).

	High volume theatre list participants	**Patients not treated on designated high volume theatre lists**	**p**
Male/female	**140/159**	**41/60**	**0.30**
1st Eye/2nd Eye	**243/56**	**87/14**	**0.29**
Right Eye/Left Eye	**164/135**	**55/46**	**1**
Age (years)	**69.45 ± 10.81**	**72.42 ± 8.6**	0.01
Pre-operative best corrected distance visual acuity (logMAR)	**0.60 ± 0.51**	**0.51 ± 0.36**	**0.10**
Spherical equivalent refractive error dioptres (D)	**-0.50 ± 4.32**	**-0.38 ± 3.52**	**0.80**
Axial length (mm)	**23.78 ± 1.39**	**23.67 ± 1.56**	**0.51**
Anterior chamber depth (mm)	**3.27 ± 0.38**	**3.10 ± 0.55**	<0.01
Average predicted PCR risk(Narendran et al., 2008)	**1.63 % ± 1.24**	**1.63 % ± 0.71 %**	**1**

Table 6.2.7-1. Demographics of patients included and excluded from the hub-and-spoke model analysis demonstrating equivalence between the two groups

The 139 patients undergoing FLACS were treated during 8 hub-and-spoke sessions, involving 16 four-hour theatre sessions. The 160 patients randomized to CPS were treated on 20 cataract theatre lists. The average OR utilisation of a hub-and-spoke session was 221mins ± 21 (92.05%±8.71) with a median of 9 patients treated in each OR, while the average duration of a CPS list was 230± 22 min (95.81%±9.17) (p<0.001) with a median of 8 patients treated per list. Patients receiving FLACS spent, a mean time of 5.85±1.99 min in the LS. 25% of FLACS theatre sessions over-ran the allotted 4 hours compared with 30% of CPS lists. Average theatre over-run was 5±2.16 min for FLACS and 13.67±8.76 mins for CPS (p=0.09).

	FLACS	CPS	p
Male/female	62/72	78/87	0.90
1st Eye/2nd Eye	111/23	132/33	0.55
Right Eye/Left Eye	70/64	94/71	0.42
Age (years)	69.07 ± 11.55	69.78 ± 10.14	0.57
Pre-operative best corrected distance visual acuity (logMAR)	0.65 ± 0.52	0.57 ± 0.50	0.18
Spherical equivalent refractive error dioptres (D)	-0.58±5.34	-0.42 ± 3.15	0.75
Axial length (mm)	23.99 ± 1.44	23.60 ± 1.33	0.02
Anterior chamber depth (mm)	3.31 ± 0.38	3.23 ± 0.37	0.07
Average predicted PCR risk(Narendran et al., 2008)	1.64% ± 0.99%	1.62% ± 1.43 %	0.89

Table 6.2.7-2. Patient demographics for the two treatment arms

Staffing levels for both models can be seen in Table 6.3-C. The hub-and-spoke model required one additional OT to be present compared with the CPS. A comparison of the average times associated with each operation can be seen in Table 6.3-D and Table 6.3-E.

	FLACS (BOTH ORS)	CPS (BOTH ORS)
OPERATING ROOMS (ORS)		
OPHTHALMOLOGISTS	3	3
OR NURSES	6.5	6.5
OPHTHALMIC DAY CARE UNIT		
OPHTHALMIC TECHNICIANS	3	2
OPHTHALMIC NURSES	2	2
RECEPTIONIST	1	1

Table 6.2.7-3. Staffing levels associated with delivery of hub-and-spoke FLACS and CPS services. ORs = Ophthalmic Operating Rooms

	FLACS (N=139)	CPS (N=160)	T TEST (P VALUE)
TIME FROM ENTERING OR TO START OF OPERATION	**5.83 ± 2.58**	**6.25 ± 2.91**	**0.19**
DURATION OF OPERATION	**12.04 ± 4.89**	**14.54 ± 6.19**	**<0.001**
TIME FROM END OF OPERATION TO EXITING OR	**2.47 ± 0.66**	**2.6 ± 1.02**	**0.20**
TOTAL TIME IN OR	**20.34 ± 5.82**	**23.39 ± 6.89**	**<0.001**
OR EMPTY	**5.27 ± 3.25**	**5.23 ± 3.28**	**0.92**

Table 6.2.7-4. Comparison of OR timings (in minutes) between hub-and-spoke FLACS and CPS based on intention to treat analysis. OR = Ophthalmic Operating Room

	FLACS (N=134)	CPS (N=165)	T TEST (p value)	FLACS CONVERTED TO CPS (N=5)
TIME FROM ENTERING OR TO START OF OPERATION	5.82 ± 2.62	6.24 ± 2.87	0.19	6 ± 1.58
DURATION OF OPERATION	11.73±3.53	14.71 ± 6.76	<0.001	20.40 ± 17.87
TIME FROM END OF OPERATION TO EXITING OR	2.47 ±0.66	2.59 ± 1.02	0.24	2.4 ± 0.89
TOTAL TIME IN OR	20.2 ±4.59	23.55 ± 7.47	<0.001	28.8 ± 19.33
OR EMPTY	5.79±3.9	5.27 ± 3.25	0.21	6.4 ± 1.95

Table 6.2.7-5. Comparison of OR timings (in minutes) between hub-and-spoke FLACS and CPS based on actual operation performed.

6.3.1. Complications

The overall rate of intraoperative complications was similar between the two groups 3.54% vs 3.76%. However, there was a noticeable difference in the rates of vitreous loss (0% with FLACS compared to 1.88% in CPS) (Table 6.3-A).

COMPLICATIONS	FLACS	CPS	RR	P
ANTERIOR CAPSULAR TEAR	3 (2.16%)	3 (1.88%)	1.15 (95% CI 0.24-5.6)	0.86
POSTERIOR CAPSULE TEAR WITH VITREOUS LOSS	0 (0%)	3 (1.88%)	0.16 (95% CI 0.01 -3.15)	0.23
DM TEAR	1 (0.72%)	0 (0%)	3.45 (95% CI 0.14 – 84.0)	0.45
SUPRACHOROIDAL HAEMORRHAGE	1 (0.72%)*	0 (0%)	3.45 (95% CI 0.14 – 84.0)	0.45
ABANDONED - EXTREME ZONULAR WEAKNESS	0 (0%)	1 (0.63%)	0.38 (95% CI 0.01-9.34)	0.56
TOTAL COMPLICATION RATE	3.54%	3.76%	0.95 (95% CI 0.30-3.07)	0.94

*Table 6.3.1-1. Incidence of complications between the two treatment arms based on intention to treat analysis. *This patient was allocated to FLACS but was unable to undergo this procedure and the patient underwent CPS (RR = Relative Risk).*

6.3.2. Economic Modelling

Based on the OR timings, using a hub-and-spoke model, we achieved a mean reduction of total time in the OR per patient of 3.05min. This allowed us to undertake one extra FLACS case per 4-hour theatre list compared to our CPS only lists. The average number of cases on using our operative models were 8 for CPS and 9 for FLACS, which represents an average 12.5% increase in productivity. We applied these results to our economic model. Based on these results, the average cost for each cataract operation was £355.42 for CPS and £500.02 for FLACS (Figure 6.3.2-A).

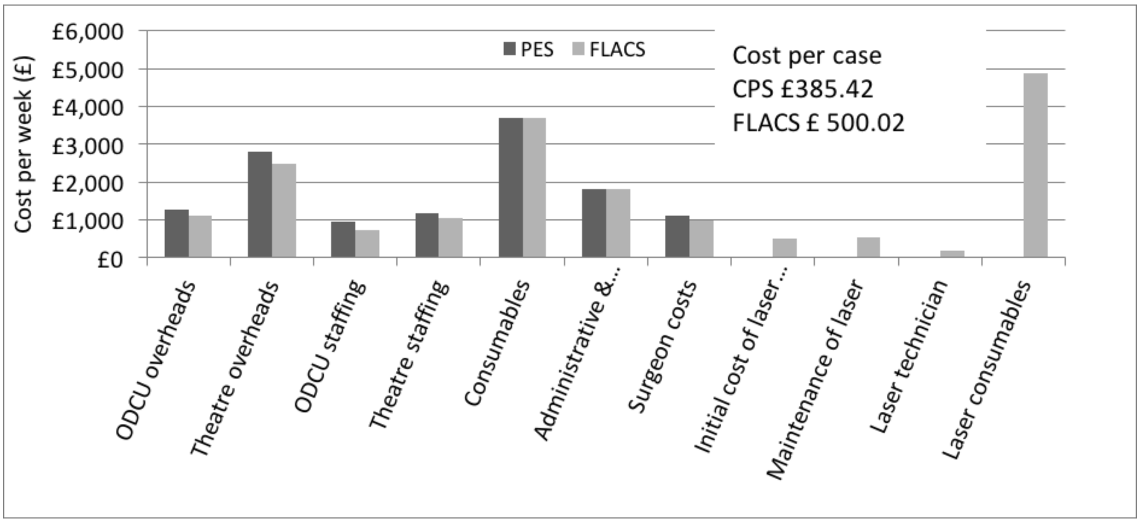


Figure 6.3.2-A Comparison of weekly costs of FLACS vs CPS services

A bivariate sensitivity analysis examining the number of cases/week and the cost of the patient interface (PI) was performed, reporting the additional cost per case of a FLACS service (Table 6.3-A).

		NUMBER OF CATARACT OPERATIONS PERFORMED/WEEK			
COST PER LASER PATIENT INTERFACE (£)		**20**	**40**	**60**	**80**
	40	£72.75	£46.51	£37.76	£33.39
	70	£102.75	£76.51	£67.76	£63.39
	100	£132.75	£106.51	£97.76	£93.39
	130	£162.75	£136.51	£127.76	£123.39

Table 6.3.2-1. Bivariate sensitivity analysis comparing effects of cost of patient interface and number of operations performed per week on the additional cost of FLACS compared with CPS within a 2:1 hub-and-spoke FLACS model.

6.3.3. 3:1 and 4:1 Hub and spoke model

Although the duration of FL application to the eye is usually between 25 and 45 seconds, patient time inside the laser room was 5.85mins ±1.99. In the model, the laser operator is an ophthalmologist working unassisted, and therefore most of time spent is on preparing the patient and setting up the laser. Based on these results, I suggest that the maximum number of ORs which could be run (to maximize the utility of a femtosecond laser) in a hub-and-spoke model would be four (average total patient time in OR + turnaround time 25.12mins±5.25). Adding a third OR to the economic modelling of the costs of cataract surgery reduced the cost per case from £500.02 to £477.28 and adding a fourth reduced it to £465.91. Performing the same bivariate analyses on a 3:1 and 4:1 hub-and-spoke models as above shows that the difference in cost could be reduced further if the hospital was performing greater numbers of cataract surgery and received a significant discount in the cost of the patient interface from the manufacturer (Table 6.3-A). However, to break even, financial modelling shows the manufacturers would need to offer between 78-99% discount on the cost of the PIs (Table 6.3-B).

			Number of operations performed per week			
			40	**60**	**80**	**100**
Cost per patient interface	**3:1 Model**	**40**	£33.40	£24.65	£20.28	£17.65
		70	£63.40	£54.65	£50.28	£47.65
		100	£93.40	£84.65	£80.28	£77.65
		130	£123.40	£114.65	£110.28	£107.65
			Number of operations performed per week			
			40	**60**	**80**	**100**
	4:1 model	**40**	£26.84	£18.10	£13.72	£11.10
		70	£56.84	£48.10	£43.72	£41.10
		100	£86.84	£78.10	£73.72	£71.10
		130	£116.84	£108.10	£103.72	£101.10

Table 6.3.3-1. Bivariate sensitivity analyses demonstrating the additional cost of FLACS compared with CPS within a theoretical 3:1 and 4:1 hub-and-spoke FLACS model when the cost of the patient interface and the number of operations per week are varied.

		NUMBER OF CATARACT OPERATIONS/YEAR				
% DISCOUNT ON COST OF PI		**2000**	**3000**	**4000**	**5000**	**6000**
	4:1 model	91	84	81	79	78
	3:1 model	96	89	86	84	82
	2:1 model	n/a	99	95	93	92

Table 6.3.3-2. Break even points for hub-and-spoke FLACS with CPS services calculated for the % discount of the patient interface based on the number of ORs concurrently run and the number of operations performed per year

6.3.4. Cases unable to undergo FLACS

Five (3.6%) patients randomised to FLACS did not receive femtosecond laser treatment. This is consistent with reported rates of unsuccessful attempts at FLACS between 2.3-6.3%(Day, Dhallu, et al., 2016; Brunin et al., 2017; J. S. M. Chang et al., 2014). In our experience, the most common reason was that the palpebral aperture was too narrow to permit the 16mm patient interface to applanate with the cornea. Four of these patients underwent uneventful CPS, with one suffering a supra-choroidal haemorrhage. This patient was considered at increased risk for this rare complication with an axial length of 19.66mm.

6.4. Discussion

When FLACS is performed within traditional models featuring one surgeon, or installing the FL in the OR, productivity may be adversely affected, leading to incurring additional indirect costs (Abell and Vote, 2014; Lubahn et al., 2014; Bali et al., 2012; Vasquez-Perez et al., 2018). This is because the duration of the patient's experience is increased with FLACS compared with CPS (time in OR + LS = 26.05 for FLACS vs 23.55 for CPS). Evaluating new models of delivering cataract surgery (such as a hub-and-spoke model) within a RCT, where patients are prospectively randomised to CPS or FLACS, allows testing of the model within a rigorous framework, rather than performing a case-control study where bias may be inherent.

By deploying a FL in the anaesthetic room adjacent to the OR and using a hub-and-spoke model, this study showed that surgical time and patient time in OR are shorter for FLACS than CPS. Transferring some of the surgical steps outside the OR using the FL reduces patient time in OR by 3.05minutes for FLACS ($p<0.001$). This led to an average of one extra operation per OR operating list of FLACS (median 9 cases per list) compared to CPS (median 8 cases per list), resulting in a 12.5% improvement in productivity (overall 2 more operations per session). Furthermore, despite the additional cases, the FLACS lists were shorter than the CPS lists, and more CPS sessions overran. The method of titrating the numbers of patients scheduled for surgery to maximise the number of operations within the four-hour session resulted in extremely high levels of OR utilisation. Our ambition to maximize theatre utilization and test the limits of the hub and spoke model, resulted in a number of theatre sessions overrunning (25% FLACS vs 30% CPS), especially when unforeseen complications had occurred. Theatre list overruns may incur financial penalty at some NHS/public hospitals..

These results are in contradiction to a comparative case series of 38 operations (19 FLACS, 19 CPS), which used instrument tracking software to calculate the amount of time and instrument movement in each stage of the cataract operation (Day et al., 2018). This study found that FLACS was on average 88 seconds longer, largely due to increased difficulty with lens cortex removal by aspiration. Limitations of this study include the relatively low number of operations and that it is a single surgeon series. Our experience found that removal of lens cortical material during FLACS is facilitated with bimanual irrigation-aspiration (I/A), which is borne out in the literature (Conrad-Hengerer, Schultz, et al., 2014), yet during the adoption of FLACS, none of the surgeons changed their preferred I/A handpiece (2 silicone co-axial, 1 bimanual) (Blomquist and Pluenneke, 2005).

A study evaluating a model of attempting to improve OR efficiency with a FL, utilised a Ziemer LDV Z8 FL, which is the only currently mobile platform and has a sufficiently small footprint to be installed adjacent to the operating table, in a single surgeon/single theatre model. This was a retrospective series of 90 patients and showed that FLACS took on average 5.2minutes±4.5 longer (Vasquez-Perez et al., 2018). Limitations include its retrospective nature, relatively smaller cohort size, and that each surgeon may have been less experienced with FLACS (only learning curve of 10 operations required). Despite this, even a FL platform sufficiently small to be positioned alongside the surgical bed, is unable to escape the general truth that a FL installed in the same operating theatre hinders efficiency (Abell and Vote, 2014; Lubahn et al., 2014).

There were some differences between the 299 patients included for this analysis and the 101 excluded, namely that the excluded group were 3 years older on average, with a corresponding shallower anterior chamber depth (ACD) by 0.17mm. It is unlikely that these differences are clinically significant and would have had a material effect on the timings of the theatre list (Narendran et al., 2008). Importantly, the prospectively calculated risk of PCR was equivalent between the two groups.

The mean time of each patient undergoing patient preparation for FL and FL application was 5.85 ±1.99 mins. Based such results it is easily possible to have a hub-and-spoke model of one FL feeding into 3 or 4 ORs (4:1 or 3:1) rather than 2 (2:1). This study suggests that the ideal number of ORs to maximize the utility of a femtosecond laser in a hub-and-spoke model would be four (average total time per patient in OR + turnaround 25.12mins ± 5.25). This would result in 3 or 4 more operations performed overall by the FLACS model per session (one for each OR).

Potential issues of having a 3:1 or 4:1 model to attempt to use a femtosecond laser as a tool for high volume surgery is that this requires a suitable and dedicated room within theatres and multiple ORs. This limits the use of such a model to an institution with such facilities already in place or a purpose-built unit (thus incurring additional costs). For instance, with a maximum of 2 ophthalmic ORs at our institution we were unable to evaluate adding additional ORs to our existing hub-and-spoke model and it would be important to incorporate any development costs in the planning process if deciding whether to adopt this technology.

To minimize costs of running the hub and spoke model it is important to minimise the additional number of staff needed. Our model required 2 additional members of staff, one ophthalmologist to operate the laser and one OT to chaperone the patients between the LS and ORs. For our CPS lists, the extra OT was not present, however there were 3 ophthalmologists between the two ORs. This may have improved the efficiency of the CPS lists in our study to a degree by allowing the surgeons to rotate. The cost of the 3rd surgeon was included in the financial modelling for the CPS model so as not to bias the model further in favour of CPS. In the FLACS model, it was also possible to permit surgeon rotation between the ophthalmologists performing laser and operating, thus possibly reducing the risk of surgeon fatigue during high volume cataract surgery.

In Chapter 3, hypothetical financial modelling of hub-and-spoke delivered FLACS was undertaken. Using a 2:1 model, bivariate sensitivity analyses showed that (for example) a 43% improvement in productivity would need to be achieved and accompanied by a 52% discount on the PI for the service to break even. This improvement in productivity was not realised by our study with a time saving of 3 minutes per patient (in the OR). The financial model demonstrates that the PI is the single most expensive item for the FLACS service. However, thus far FL platforms have tended to be used, and marketed as a premium product (based on reported improved refractive outcomes and stability) (Conrad-Hengerer et al., 2015). However it is very likely that a public health care service may be able to negotiate discounts on the costs of FLACS, especially if used within a high-volume service (which further improves affordability) (Table 6.3-A and Table 6.3-A). Further cost savings may be made by improved safety which may make cost savings in post-operative management (Qatarneh et al., 2012). The FL may bring other advantages to a department, such as adding corneal surgical capabilities. It is important to note therefore that whilst there was no difference in posterior capsular rupture (PCR) and vitreous loss rates in this arm of the present study to investigate comparative high-volume hub-and-spoke FLACS and CPS theatres lists (table 7), the results of the chapter 5 RCT showed a statistically significant reduction in PCR with FLACS. As such complications incur additional costs, if our findings with respect to PCR rates are replicated by others, then our economic modelling might be more favourably inclined toward a FLACS hub-and-spoke model.

Investigation of the effects of number of AHPs assisting in cataract theatre lists on the overall productivity showed a marked difference in the number of cataract surgeries performed between different institutions, but furthermore that a minimum of 4 AHPs are required to deliver high volume cataract surgery with effective use of theatre time and minimum delays (Chapter 2) (H. W. Roberts MSc FRCOphth, Myerscough, et al., 2017). The cataract theatre lists at St Thomas' are generally run with 3 AHPs, which precludes further increases in productivity, which is evident in our turnaround time compared with other surgical units. The average time between one operation finishing and the start of the next was 13.57min and 14.08min for FLACS and CPS respectively, meaning that only between 47.0 - 50.8% of OR time is spent engaged in surgery. Our previous time and motion studies showed that patient turnover with 4 AHPs present can be reduced to 9.70mins within NHS units. Including one additional AHP per OR to our unit (at a cost of £70 per session) to facilitate patient turnover could possibly provide a greater overall time saving than this FLACS hub and spoke model.

6.4.1. Limitations

This study considered the productivity difference in terms of number of operations per OR and found a 12.5% improvement in FLACS. However other methods of assessing productivity could have been chosen (for example number of cases per surgeon). However, there are usually an abundance of cataract surgeons in a department compared with theatre time and space, making the latter more of a limiting factor. The department did not incur any infrastructure costs in the installation of the laser into the anaesthetic room and so it was not possible to provide a representation of infrastructure costs into the model. However, other surgical units have incurred significant costs during the installation of a FL, so this is an important consideration. The surgical team was not masked to the treatment arms and this may be associated with performance bias. Another potential source of bias is that we had to book patients to theatre lists pre-emptively; having a busier list may have improved productivity. Nevertheless, we aimed to combat this by a fair and transparent method of a run-in period before the trial commenced to build experience with the model and titrating booking numbers in an objective way depending on previous early finishes and overrunning. These potential biases may have been even more evident within a cohort study methodology, hence why a RCT was preferred.

6.5. Conclusion

In summary, FLACS with a hub-and-spoke model was significantly faster than CPS, with patients spending less time in the OR. This enabled a slight improvement in productivity, but not sufficient to meaningfully offset the additional costs relating to FLACS. Further gains in productivity may have been achieved with a 3:1 or 4:1 hub-and-spoke model.

Chapter 7. Refractive outcomes after limbal relaxing incision or femtosecond laser assisted astigmatic keratotomy in the management of corneal astigmatism at the time of cataract surgery

Supplementary Material #5. Roberts, H.W., Wagh, V.K., Sullivan, D.L., Archer, T.J. and O'Brart, D.P., 2018. Refractive outcomes after limbal relaxing incisions or femtosecond laser arcuate keratotomy to manage corneal astigmatism at the time of cataract surgery. Journal of Cataract & Refractive Surgery, 44(8), pp.955-963.

7.1. Introduction

LRIs or FS-AKs have been found to be efficacious in the management of low to moderate astigmatism (<2.5-3D) but are less suitable for moderate to high astigmatism which require toric IOLs or bioptics (Day, N. M. Lau, et al., 2016; Nanavaty et al., 2017). To my knowledge there are no trials comparing the effectiveness of LRIs with FS-AK in the management of low to moderate corneal astigmatism at the time of cataract surgery. The purpose of this study was to investigate any differences between laser and manually delivered keratotomies using vector analysis (Alpins, 2001; Alpins and Goggin, 2004; Alpins, 1993; Reinstein et al., 2017).

7.2. Methods

This analysis of refractive outcomes of patients treated with LRIs or FS-AKs was performed as a secondary outcome of a prospective randomised interventional case-controlled study at a single University Hospital (Guy's & St Thomas' Hospital NHS Foundation Trust, London, UK) to assess the relative costs of delivering a FLACS service compared with CPS (Clinicaltrials.gov registration number NCT02825693). The study was approved by local Research & Development and Cambridge South Research Ethics Committee (reference 16/EE/0180). This study was conducted adhering to the tenets of the Declaration of Helsinki.

Methods of the study have been described in Chapter 5. Four hundred eyes of 400 patients were randomised to receive FLACS or CPS. FLACS treatment was performed using the LenSx Femtosecond laser (Alcon Inc,). The femtosecond laser was used to perform capsulotomy, lens fragmentation in all patients and intrastromal FS-AK when appropriate. All cataract operations were performed under local anaesthetic. Following FL treatment, the patient was transferred to the operating theatre for the remainder of the cataract extraction. Phacoemulsification was performed using the Infiniti phacoemulsification machine (Alcon Inc) in both groups. Patients undergoing CPS were prepared for surgery in the same way as those in the laser arm. Instead of receiving laser pre-treatment, they were brought straight to theatre and received LRIs at the start of the cataract operation. All operations were performed by experienced surgeons who had completed at least 30 FLACS procedures (HWR, VKW, DOB).

Specific to this sub-group analysis, any patient with corneal astigmatism greater than 0.9D based on Pentacam Tomography (Oculus, Germany) were offered LRI or FS-AK as part of their cataract operation based on the initial randomisation. Eyes with previous refractive or corneal surgery, or corneal pathology were excluded. The IOL Master 500 (Carl Zeiss Meditec AG, Switzerland) provided keratometry measurements used for IOL formula calculation. Corneal astigmatism was measured using Pentacam topography and were used for pre-operative astigmatism planning and post-operative analysis. Where biometry was not possible on IOL Master 500 owing to density of cataract, an A-scan ultrasound biometry (Carl Zeiss Meditec) was performed. All post-operative results were recorded at 4 weeks follow up.

7.2.1. LRI group

LRI parameters were calculated based on Donnenfeld's nomogram via an online software (Abbott Medical Optics, USA; available at https://www.lricalculator.com). This nomogram requires the age of the patient, steep and flat K values with axies, the location of the main CCI and the surgeons SIA. We based our nomogram inputs on the keratometric readings from Pentacam and individual surgeon's surgically induced astigmatism (SIA) values. Target induced astigmatism (TIA) was always aimed at 100% correction. Paired arcuate LRIs were always performed; where the surgeon's preference was to operate on axis, the 2.4mm main wound was positioned in the middle of the LRI. When anatomy or comfort dictated an off-axis approach, the surgeon's SIA was used to modify the LRIs.

Manual limbal markings at 0° and 180° were made for all eyes (LRI and FS-AK groups) preoperatively with patients in sitting position at the slit lamp with a needle to scratch the corneal epithelium at the limbus, followed by a sterile marker pen.

A Mendez-style ring was used to mark the steep meridians at the start of the surgery. The LRI incision was made before the commencement of phacoemulsification using a 2.4mm keratome to incise through epithelium and Bowman's layer, followed by a 600μm guarded diamond knife to incise through the stroma. No corneal sutures were used during the surgery.

7.2.2. FS-AK group

FS-AK parameters were determined by a nomogram previously reported by Day et al (Day, N. M. Lau, et al., 2016). The settings of the FL for the arcuate intrastromal incisions were also maintained. Although this nomogram was intended to achieve only up to 70% correction, for ease of interpretation of outcome data, the TIA was defined as an 100% correction with no residual postoperative corneal astigmatism. After docking with the FL, manual adjustment of the horizontal meridian was performed when cyclo-rotation had occurred

(Hummel et al., 2017). In cases where either of the AKs overlapped with the surgeons planned manual wound, the main section would be positioned more peripherally than the AK so that it would not be involved.

7.2.3. Statistics

Baseline characteristics were summarized for each treatment arm. Results were analysed primarily as per intention to treat. For all evaluations of visual acuity as an outcome, patients with visually significant ocular co-morbidities were excluded prospectively and those opting for a refractive target other than emmetropia were excluded from analysis of refractive outcome. Snellen visual acuities were converted to logMAR for analysis (Lange et al., 2008). Comparative and descriptive statistical analyses included the Fisher exact test, chi-square test, and Student t tests. All statistical tests used a two-sided p value of α=0.05 unless otherwise specified. Excel software (Microsoft Corp.) was used for data entry, analysis and graphical representation. Intra-operative or post-operative complications were defined as any event that involved unintentional trauma to an ocular structure, requiring additional treatment, or having a negative effect on participants' eyesight.

Analysis of corneal astigmatic outcomes based on corneal topography measurements before and after surgery were performed using the Alpins method, with calculation of 3 vector parameters: target induced astigmatism (TIA), surgically induced astigmatism (SIA), and difference vector (DV) (Alpins, 2001; Alpins and Goggin, 2004; Alpins, 1993). TIA is defined as the intended correction in astigmatic magnitude and axis, SIA is the amount and axis of astigmatic change achieved by surgery and the DV is the magnitude and axis of the residual astigmatism. Results are presented based on the standardized graphs for reporting the outcomes of refractive surgery and IOL based refractive surgery (Reinstein et al., 2017; 2014). Additional parameters calculated include the correction index (CI), angle and magnitude of error and the index of success (IoS). The CI is a ratio of the SIA divided by the TIA, where values greater than 1 indicate overcorrection, and less than 1, undercorrection. The angle of error is the difference in angle between the SIA and TIA. The IoS is the DV divided by the TIA with a value of 0 indicating perfect correction. The axis of the steep meridian has been used throughout.

7.3. Results

Four hundred and twenty-seven patients were recruited to the study between August 2016 and June 2017 as per the inclusion/exclusion criteria (Table 7.3-A). Twenty-seven patients withdrew from the trial before surgery. Four hundred eyes of 400 patients received surgery between November 2016 and June 2017 (200 CPS, 200 FLACS).

	LRI	FS-AK	p
Age (years)	72.5 ± 10.5	69.7 ± 12.0	0.21
Sex (% female)	56.8%	41.5%	0.24
Laterality (% right eyes)	55.0%	53.8%	1.0
Pre-operative best corrected distance visual acuity (logMAR)	0.45 ± 0.38	0.69 ± 0.52	0.01
Pre-operative arithmetic mean spherical equivalent refractive error (D)	0.81 ± 2.88	-1.4 ± 4.51	0.004
Pre-operative absolute mean spherical equivalent refractive error (D)	2.69 ± 2.48	3.25 ± 3.24	0.32
Pre-operative cylindrical refractive error (D)	-1.42 ± 0.79	-1.34 ± 0.99	0.65
Axial length (mm)	23.56 ± 1.37	24.26 ± 1.69	0.02
Preoperative corneal keratometry (Kmax) (D)	44.42 ± 1.33	43.98 ± 1.59	0.13
Preoperative corneal astigmatism (Kdiff)/Target Induced Astigmatism Vector (TIA) (D)	1.50 ± 0.46	1.38 ± 0.40	0.16
Summated vector mean	0.31 Ax 160	0.21 Ax 174	

Table 7.2.3-1 Patient demographics and baseline values. (D= Dioptre, logMAR = logarithm of minimum angle resolution)

A total of 51 eyes of 51 patients in the CPS group received LRIs of which 8 were excluded from analysis of UDVA for visual comorbidities (age related macular degeneration/AMD n=6, amblyopia n=1, chronic central serous chorioretinopathy n=1). A total of 53 eyes of 53 patients in the FLACS group received FS-AK of which 9 were excluded for visual comorbidities (AMD n=4, amblyopia n=2, previous retinal detachment n=1, vitreomacular traction n=1, central retinal vein occlusion n=1).

Astigmatic Vectoral Analyses	LRIs		FS-Aks		p
	Mean	S.D.	Mean	S.D.	
Target Induced Astigmatism Vector (TIA) (D) Arithmetic mean	1.50	0.46	1.38	0.40	0.16
Summated vector mean	0.31 Ax 160		0.21 Ax 174		
Surgically Induced Astigmatism Vector (SIA) (D) Arithmetic mean	1.02	0.91	1.23	0.77	0.21
Summated vector mean	0.07 Ax 161		0.16 Ax 93		
Correction Index (CI) Geometric mean	0.48	0.57	0.73	0.49	0.02
Difference Vector (DV) (D) Arithmetic mean	1.17	0.69	0.89	0.54	0.02
Summated vector mean	0.25 Ax 160		0.37 Ax 178		
Index of Success (IOS) Geometric mean	0.81	0.49	0.65	0.4	0.07
Angle of Error (A of E) (deg) Arithmetic mean	-3.35	29.90	2.35	25.95	0.30
Absolute mean	22.10	20.19	17.99	18.69	0.28

Table 7.2.3-2 Vector analysis of post-operative results

Case demographics and pre-operative values can be seen in Table 7.3-A. There were some statistically significant differences at baseline between the two groups: namely worse visual acuity (7 letters), and longer axial length (by 0.7mm) in the femtosecond group. TIA & SIA single angle vector plots are displayed in Figure 7.2.3-A and Figure 7.2.3-B. SIA was less than TIA in both groups indicating under-correction. However, the FS-AK corrected more astigmatism than the LRI as the CIs were 0.73 and 0.48 respectively (p=0.02). The DV was also lower in the FS-AK group (p=0.02) indicating better correction (Table 7.3-B, Figure 7.2.3-C and Figure 7.2.3-D). Despite a greater SIA, CI and lower DV, there was not quite a statistically significant difference in the Index of Success (ratio of DV to TIA) between the two groups (p=0.07). Angles of error and TIA versus SIA graphs are in Figure 7.2.3-E and Figure 7.2.3-F. The 4 standard graphs for representation of refractive outcomes of cataract surgery are seen in Figure 7.2.3-G, Figure 7.2.3-H, Figure 7.2.3-I and Figure 7.2.3-J. In both groups, nearly 60% of patients attained their visual potential without needing refractive correction (figure 8). 20% of LRI patients and 44% of FS-AK patients attained post-operative cylinder of <0.5D (p=0.01) and 44% vs 74% respectively had less than 1D cylinder (p=0.003) (Figure 7.2.3-J). Corneal astigmatism was reduced in the FS-AK group from 1.38D±0.40 to 0.89D±0.54 and from 1.50D±0.46 to 1.17D±0.69 in the LRI group (p=0.02). Post-operative refractive cylinder was 0.90D±0.50 and 1.18D±0.90 respectively (p=0.05). The arithmetic mean of the angle of error was very small in both groups indicating neither group had an overall misalignment of treatment. However, the absolute mean indicates a misalignment of 18 - 22 degrees (p=0.28). (Table 7.3-B).

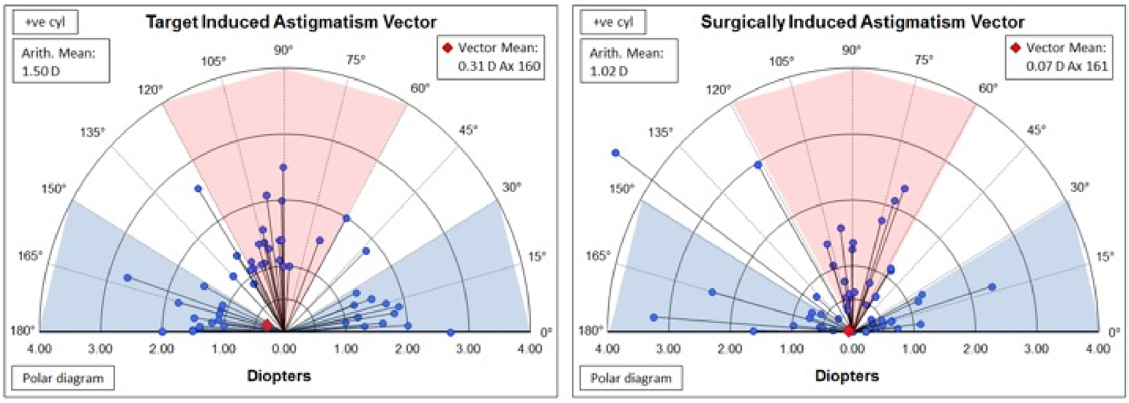


Figure 7.2.3-A Single angle polar plots regarding corneal astigmatism for target induced astigmatism (TIA) and surgically induced astigmatism (SIA) of the patients treated with limbal relaxing incisions (LRI).

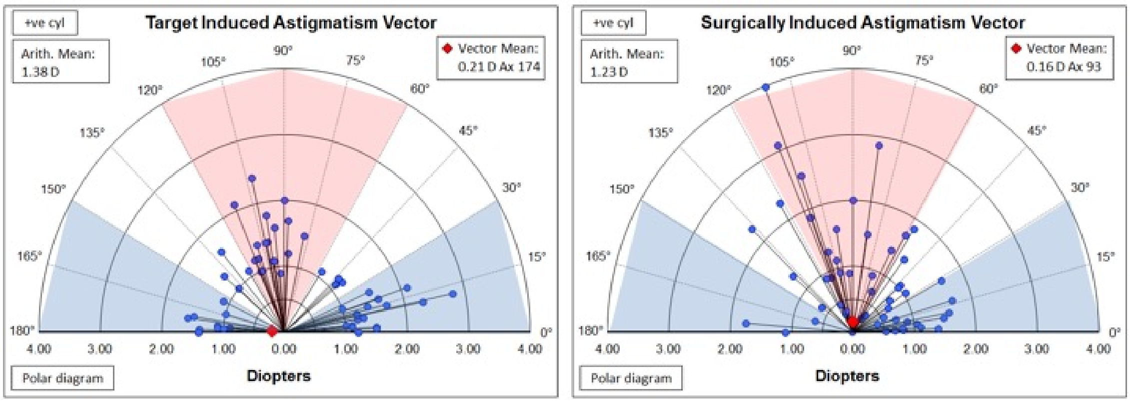


Figure 7.2.3-B Single angle polar plots regarding corneal astigmatism for target induced astigmatism (TIA) and surgically induced astigmatism (SIA) of the patients treated with femtosecond laser astigmatic keratotomies (FS-AK).

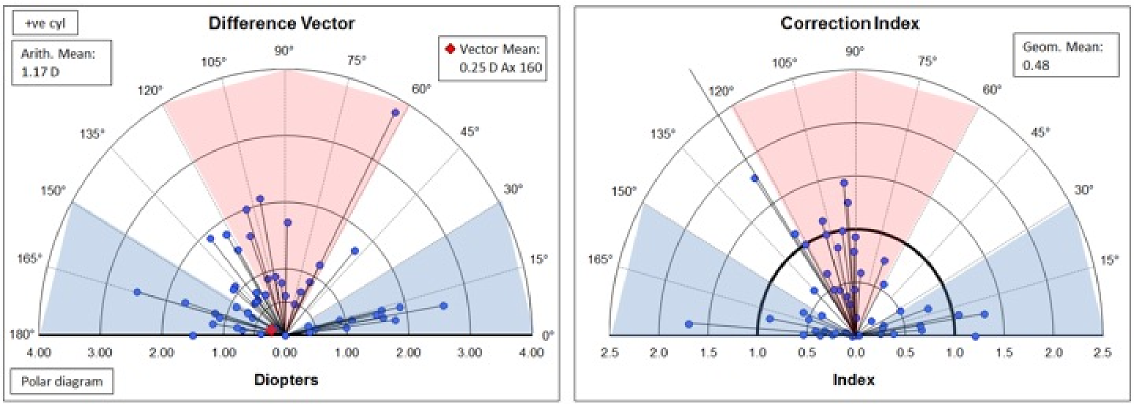


Figure 7.2.3-C Single angle polar plots regarding corneal astigmatism for difference vector (DV) and correction index (SIA) of the patients treated with limbal relaxing incisions (LRI). One outlier is not represented on the correction index graph – the correction index graph – the correction index of 3.38 is off the scale of the chart.

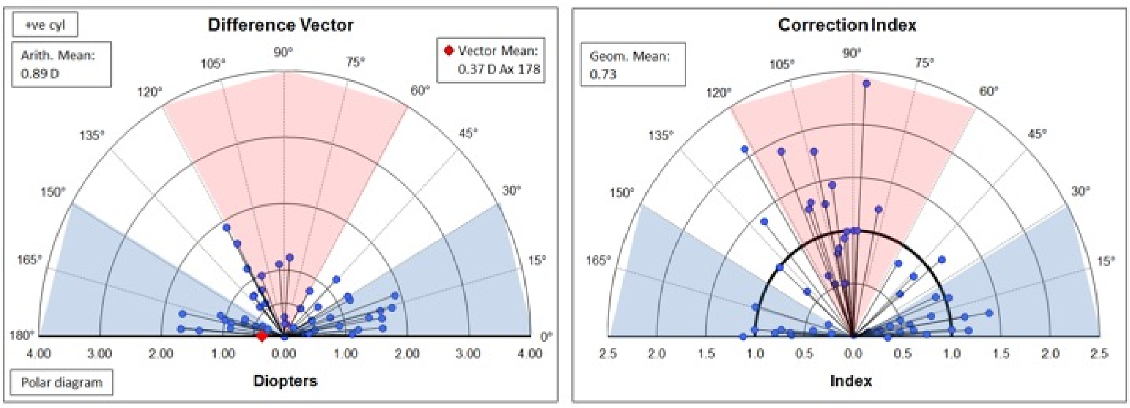


Figure 7.2.3-D Single angle polar plots regarding corneal astigmatism for difference vector (DV) and correction index (SIA) of the patients treated with femtosecond laser astigmatic keratotomies (FS-AK).

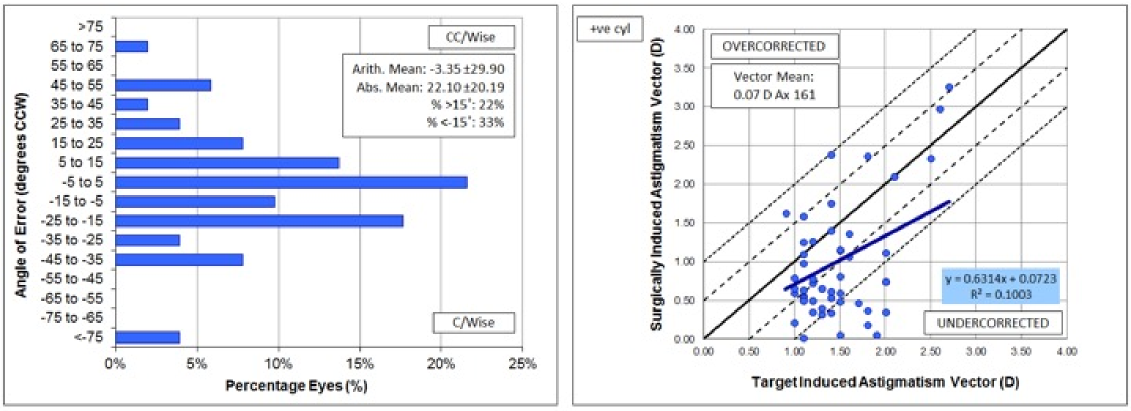


Figure 7.2.3-E The astigmatism angles of error and the TIA vs SIA graphs of the patients treated with limbal relaxing incisions (LRI).

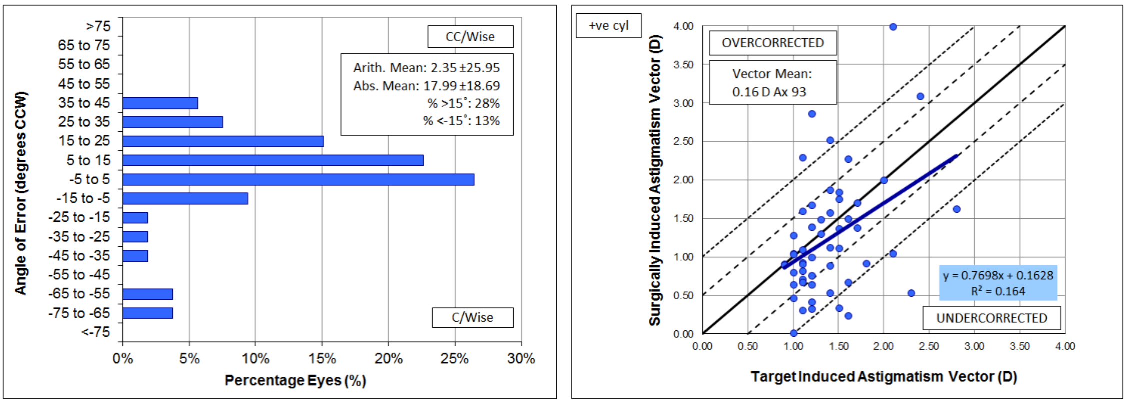


Figure 7.2.3-F The astigmatism angles of error and the TIA vs SIA graphs of the patients treated with femtosecond laser astigmatic keratotomies (FS-AK).

FL treatment was delivered successfully to 100% of cases. There was a complication relating to laser delivery in 5 cases (9.4%), which included: corneal abrasion (n=2, 3.7%), incomplete capsulotomy (n=3, 5.6%). The FL treatments delivered were corneal incisions (0%), capsulotomy (100%), lens fragmentation (100%) and arcuate keratotomies (100%). Limbal relaxing incisions were performed in the CPS group in all cases. None of the FS-AKs or LRIs resulted in any complication including posterior perforation or inadvertent placement. Intraoperatively, 2 patients in the FS-AK group sustained an anterior capsular tear and one patient had intraoperative floppy iris syndrome (IFIS), 2 patients in the LRI group had IFIS and one had iris prolapse/trauma. Post-operatively none of the LRI group suffered complications, 2 patients in the FS-AK group had CSMO and one had a steroid response causing an intraocular pressure of 30mmHg at 4 weeks.

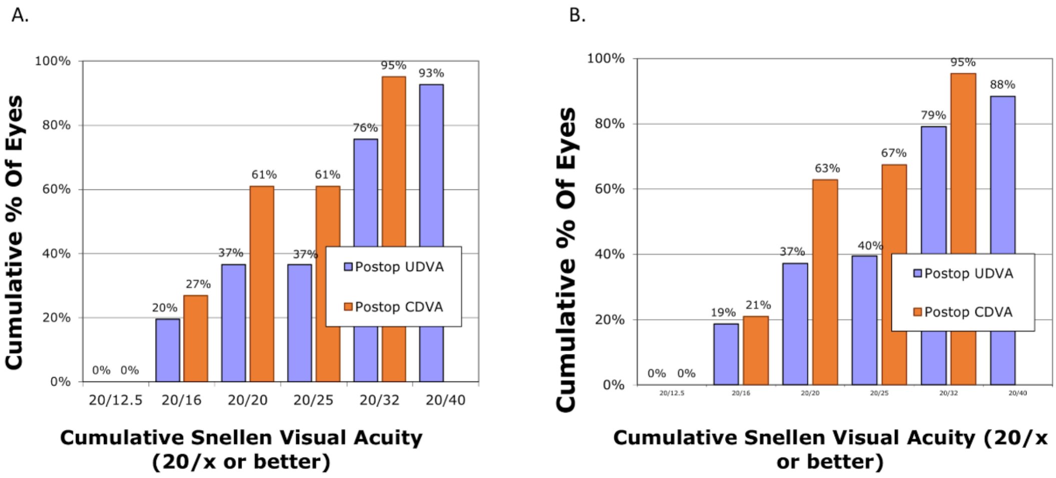


Figure 7.2.3-G (A&B) Cumulative percentages of postoperative Snellen visual acuity (unaided distance and corrected distance) of A) limbal relaxing incisions and B) femtosecond laser astigmatic keratotomies.

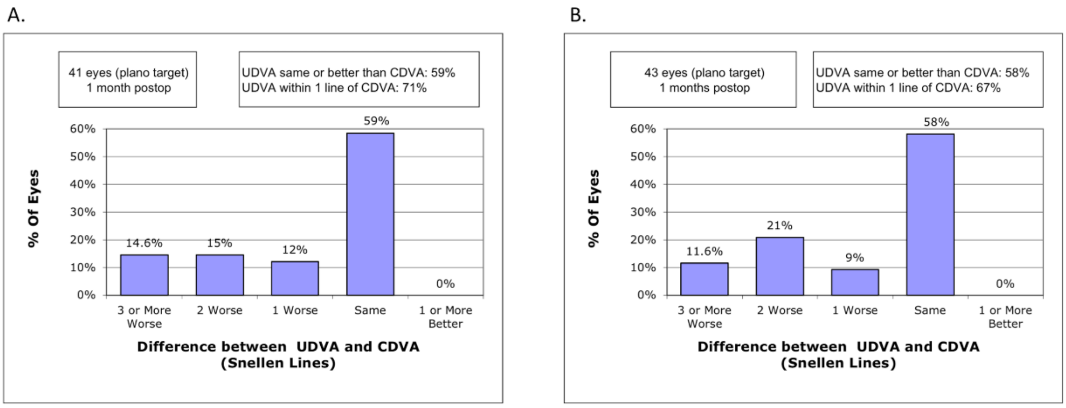


Figure 7.2.3-H (A&B): Number of lines difference between unaided and corrected distance visual acuity of A) limbal relaxing incisions and B) femtosecond laser astigmatic keratotomies.

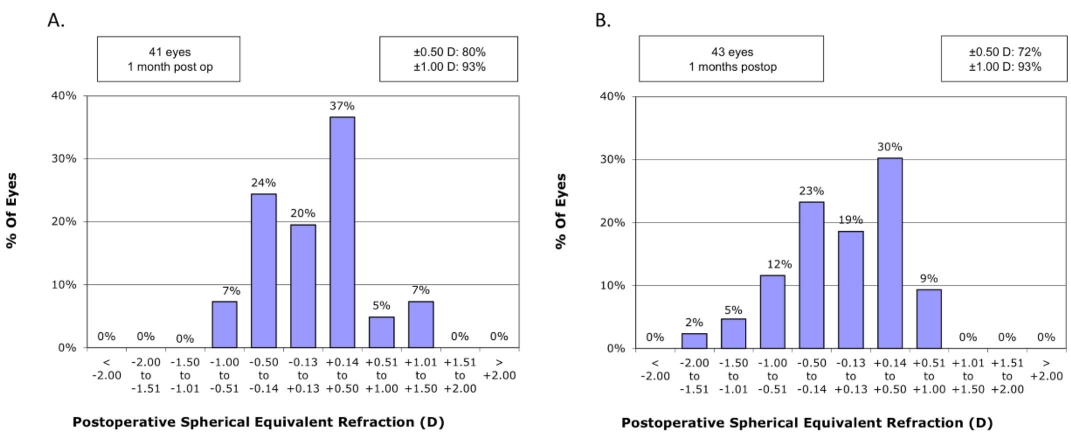
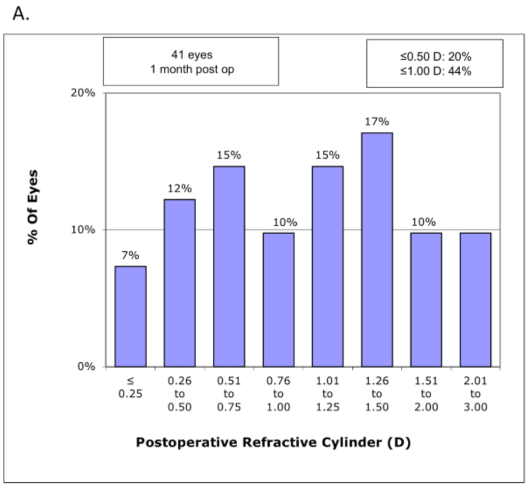


Figure 7.2.3-I (A&B): Spherical Equivalent Refractive Accuracy of A) limbal relaxing incisions and B) femtosecond laser astigmatic keratotomies.



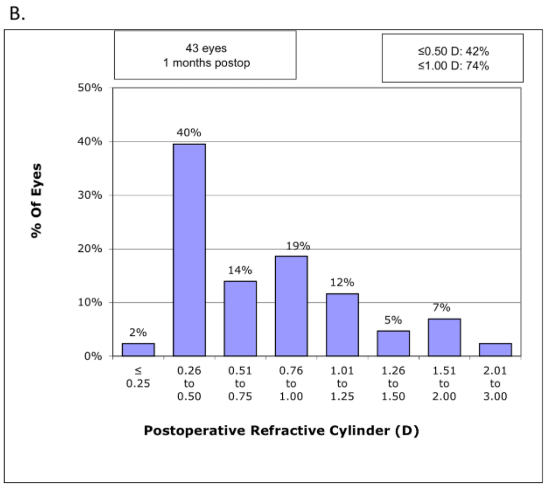


Figure 7.2.3-J (A&B): Pre-operative and post-operative refractive astigmatism of A) limbal relaxing incisions and B) femtosecond laser astigmatic keratotomies.

Sub-group analysis

A subgroup analysis was performed on those with 0.9-1.5D cylinder preoperatively (Table 7.2.3-3). The FS-AK group continued to have the superior SIA (1.1 vs 0.92, p=0.28), CI (0.91 vs 0.74, p=0.19) and lower DV (0.78 vs 1.02, p=0.08) and IoS (0.66 vs 0.83, p=0.2), however none of these results were statistically significant.

	CPS (N=35)		FLACS (N=40)		
	mean	SD	mean	SD	p
TIA (ARITHMETIC MEAN)	1.24	0.18	1.2	0.18	0.33
SIA (ARITHMETIC MEAN)	0.92	0.84	1.1	0.62	0.28
CORRECTION INDEX	0.74	0.63	0.91	0.49	0.19
DIFFERENCE VECTOR	1.02	0.67	0.78	0.5	0.08
INDEX OF SUCCESS	0.83	0.54	0.66	0.44	0.2
ANGLE OF ERROR	18.86	17.72	17.9	19.38	0.82

Table 7.2.3-3 Vector analysis of post-operative results for those with 1.5DC or less pre-operatively.

7.4. Discussion

The femtosecond laser can perform, with reliability and reproducibility, several important steps of cataract surgery. This includes arcuate keratotomies, which are performed to reduce corneal astigmatism at the time of surgery. While the effects of laser capsulotomy on IOL centration and refraction as well as the effects of lens fragmentation on total phacoemulsification energy have been previously investigated, this is the first study to investigate the efficacy of automated femtosecond AKs compared to manual LRIs during cataract surgery. Both techniques have been previously shown to be efficacious at reducing corneal astigmatism, but have not yet been directly compared (Day, N. M. Lau, et al., 2016; Müller-Jensen et al., 1999).

In this study, we used the FS-AKs nomogram as originally described by Day et al (Day, N. M. Lau, et al., 2016), notwithstanding two important differences. Firstly, we utilized a different femtosecond laser platform and secondly, unlike Day's group where the main incisions were consistently temporal, we elected to perform our main incisions on axis whenever possible (accounting for surgical access etc). Using this methodology, we found that FS-AK had a greater correction index than LRI, indicating that SIA was 73% of TIA (compared with 48% for LRI). For the purposes of analysis TIA of the FS-AK group was assumed to be a 100% correction but it is important to note that the nomogram for the FS-AK aims for a 70% correction to avoid too many patients being overcorrected and therefore the FS-AK was remarkably accurate in what it aimed to deliver (Day, N. M. Lau, et al., 2016). It might be assumed therefore that aiming for a 100% correction with FS-AK with on axis incisions might deliver better astigmatic correction than these currently presented results and should be the subject of further clinical studies and nomogram refinement.

A subgroup analysis was performed of those with 1.5DC of preoperative corneal cylinder or less (Table 7.2.3-3). With techniques such as LRIs or FS-AKs offering astigmatism correction in cases of low to moderate corneal cylinder, many surgeons will opt to use toric IOLs in those with above a certain threshold of corneal astigmatism(Lam et al., 2015), with individual surgeons commonly opting for cut offs of 1DC, 1.25DC or 1.5DC. With our inclusion criteria requiring patients have >0.9DC, we were able to perform vector analysis excluding those with such significant astigmatism that these patients would commonly be offered a toric IOL. This did not show a statistically significant benefit of FS-AK over LRI. While both techniques had greater undercorrection with larger TIAs, they were more closely matched for lower magnitudes of astigmatism (Figure 7.2.3-E and Figure 7.2.3-F).

Further areas for refinement include the accuracy of the femtosecond laser incisions, the better understanding of corneal biomechanics in the context of FS-AKs and the effects of the FS-AK on the posterior corneal curvature. A recent optical coherence tomography study of FS-AKs demonstrated that the midpoint depth of the intrastromal incisions were significantly more anterior than the planned parameters and that the locations of the paired intrastromal incisions in each eye were not correlated (L. Wang et al., 2017). Investigations of biomechanical properties and factors contributing to outcomes of FS-AK have shown that the type of astigmatism (against the rule, with the rule or oblique) are independent predictors of the efficacy of FS-AK and that corneal hysteresis has a negative correlation with the SIA at 1-6 months (Day and Stevens, 2016a; Byun et al., 2018). Löffler et al. demonstrated that FS-AKs have effects on the anterior corneal curvature and total corneal refractive power but not the posterior curvature (Löffler et al., 2017). A study of 50 eyes treated with FLACS and single 8mm FS-AKs showed an increase in coma, trefoil and higher order aberrations post-operatively (T. C. Y. Chan et al., 2016).

It is important to note that in this study, there were no significant differences in the absolute or arithmetic mean angle of error. This implies that femtosecond laser AKs are no better aligned than can be achieved manually. Interestingly, the FS-AK group had a significantly smaller mean difference vector (the residual correction required to achieve the TIA) and yet the index of success was not quite statistically significant between the two groups. The index of success is defined as the difference vector divided by the TIA, where a number closer to zero indicates greater success and the value for the LRI group was 0.81 compared with 0.65 for the laser group ($p=0.07$). This could therefore possibly be explained by TIA of the LRI group being 0.12D greater.

In addition to our findings that FS-AK had a greater correction index than LRI, there appear to be several advantages of FS-AKs over limbal relaxing incisions. Firstly, they only take a few seconds to program into the laser platform and for the laser platform to undertake them. In addition, although in this study we marked all eyes at the slit-lamp pre-operatively, with several FLACS platforms now allowing integration with corneal topography/tomography devices and featuring iris or conjunctival vessel recognition, pre-operative marking of the axis is becoming redundant (Hummel et al., 2017), further enhancing both patient and surgeon convenience as has been possible with the implantation of toric IOLs (Webers et al., 2017). Finally, as the incisions are intrastromal, there may be reduced postoperative discomfort compared with LRIs and less chance of posterior/full thickness perforation, infection or inflammation. However, it is important to note that there are significant additional costs associated with femtosecond laser technology, but only limited additional cost and materials are required to perform the AKs.

One key limitation of this study is that follow-up was limited to the first post-operative month and that longer-term efficacy was not evaluated. The published literature reports variable results in terms of the regression of the effects of LRIs with time, although generally such corrections appear to be relatively stable after the first post-operative month (Lim et al., 2014). In a series of 263 patients by Day et al., of which 87 had received intrastromal astigmatic keratotomies, regression in SIA was only 0.1D between 1 and 6 months and equivalent between groups which did or did not receive AKs (Day and Stevens, 2016b). Similarly, Chan et al. demonstrated stability of astigmatic correction by AK between 2 months to 2 years post-operatively (T. C. Y. Chan et al., 2016) and a series of 89 eyes by Byun et al showed no significant changes between 2 and 6 months (Byun et al., 2018). This suggests that astigmatic corrections achieved at one month are a good indicator of efficacy, although we are following up these patients at 12 months to assess longer term efficacy.

Interestingly, despite randomization there were some statistically significant differences at baseline between the two groups: namely worse visual acuity (7 letters), and longer axial length (by 0.7mm) in the femtosecond group. However, there were no differences of the pre-operative astigmatism or the keratometry. We believe that the differences in vision and axial length do not play a significant role in the analysed outcome parameters in this current study.

In summary, we found that both manual limbal relaxing incisions and femtosecond laser intrastromal arcuate keratotomies were safe and easy to perform, with both achieving a meaningful reduction in corneal astigmatism. However, the laser group achieved a correction of greater magnitude than the limbal relaxing incision cohort at 4 weeks after surgery. The greatest differences occurred in cases with larger TIAs and a subgroup analysis of those with <1.5DC demonstrated no statistically significant differences.

Chapter 8. Conclusions

8.1. Summary

The aim in this thesis has been to appraise the possible role of FL technology with regards to cataract surgery in the NHS. To gain a better understanding of variables important to the efficiency of a cataract surgical session I began by performing a TMS (Chapter 2). Contrary to confirming the importance of the length of the operation (usually the metric most commonly reported in other studies evaluating productivity), this study demonstrated several inefficiencies of public sector based cataract surgery unrelated to the surgeon. Firstly, the variation in productivity and under-utilisation of theatre time, between routine NHS theatre lists and NHS surgeons with a special interest in high volume cataract surgery or the private sector. Secondly, the role of the AHP in productivity and that staffing levels of less than 3 AHPs creates a rate limiting step in the turnaround time between operations. Finally, the number of distractions to the surgeon and number of non-surgical tasks delaying the theatre list and preventing them from performing surgery during the allotted theatre list time, suggest that delegation of non-surgical tasks to trained AHPs is important band can greatly improve productivity as had occurred in the private hospital setting. The intention was to use the results of this TMS to better understand efficient or inefficient practices in the cataract service at Guy's and St Thomas' NHS Foundation Trust, before the introduction of a high-volume hub and spoke FLACS service.

Discussions regarding cost effectiveness or profitability of FLACS typically focus on the capital outlay for the device itself (Abell and Vote, 2014; Trigueros et al., 2016). One of the advantages of conducting some preliminary financial modelling in advance of a FL RCT was to understand better the relative importance of different financial factors in a FL centred service (Chapter 3). The most striking realisation of the financial modelling undertaken, was the relative inconsequence of the cost of the FL compared with the overwhelming cost of the single-use PIs, which became the single most expensive item in a hypothetical FL service. As this cost was applied to every case, a so-called pay-per-click fee, no improvements in efficiency could offset this financial burden. Therefore, the idea of high volume FLACS offsetting its own costs would be a near impossibility, without some discount in the price of the PIs.

A key concern in the planning of the RCT methodology was the effects of the learning curve of FLACS on any potential bias on the results of the study in favour of CPS. In particular I was aware of increased risk of anterior capsular tear within the learning curve (T. V. Roberts et al., 2013; Abell, Kerr, and Vote, 2013a). In planning the RCT, it was necessary to ensure that the other two surgeons and I had completed enough cases to avoid an increased rate of complications in the FLACS cohort. There was no consensus on the length of the learning curve in the published literature. Based on a review of the literature, I planned for each surgeon to have completed 30 cases before the start of the RCT, but the results of all FLACS were collected allowing for a retrospective evaluation of the learning curve using CUSUM. The profiles of the three surgeons was heterogeneous from an extremely senior surgeon to myself, with 3 years and 300 cases of previous cataract surgery experience before commencing this research fellowship. CUSUM analysis demonstrated pooled stability in rates of PCR after the 16th case (Chapter 4). This is relevant not only in the planning of future FLACS trials, but also in the supervision of surgeons new to FLACS.

The FLACS RCT is larger than any previously published RCT(H. W. Roberts MSc FRCOphth et al., 2019). The 16 RCTs in the Cochrane Review analysed were generally underpowered (Day, Gore, et al., 2016). Furthermore, 11/16 studies were rated as having an unclear or high risk of bias. This study has been funded by the manufacturer, but by a non-commercial grant with the Funder having no input into the running or analysis of the study. The results of the RCT were noteworthy in their equivalence between the two techniques. The most significant result we found was a difference in the PCR rate. However, this is open to interpretation for various reasons including the marginal significance and the number of t-tests performed. Clinically, at least, the two other surgeons and I agree that FLACS is certainly an easier, more automated, technique for cataract surgery. We noticed a difference in our fatigue levels after a high volume FLACS list compared with CPS. We think this may translate into fewer surgical complications. Reduced complication rates, most notably PCR, are borne out in several published papers, however, are not reflected overall by the meta-analyses. One limitation of the literature is that outcomes may improve due to the continual refinement of the FL technology, mostly in software updates, for example as per the difference in anterior capsular tear rate with the Catalys FL as the software was upgraded to improve the speed of capsulotomy (Day et al., 2014; Abell, Kerr, and Vote, 2013a). It is conceivable that grouping older studies with more recent publications in a meta-analysis may hide any clinical benefit from FL as the technology and clinical experience have improved. Equally, we did not derive any improvement in visual acuity or refractive outcome in the FLACS group, and we question whether a FLACS capsulotomy does result in a clinically meaningful improvement in lens decentration or tilt, although it is important to note that the follow up in our RCT was only 4 weeks. Neither was any benefit reflected by the 2 PROM questionnaires. In summary, it is an important result that there appears to be clinical equivalence between FLACS and CPS, it is unlikely to have worse outcomes as has been suggested in the EUREQUO study (Manning et al., 2016). Anecdotally, the FL at St Thomas' since the end of the study has been involvement in further studies as well as some complicated cases but is not used, outside further research trials, for routine cataract surgery. In reflection, the FL may have a role in some academic/tertiary centres with a significant cohort of complicated cataracts and clinic research aspirations, but it unlikely to be of widespread relevance to the NHS in terms of clinical outcomes.

Regardless of the clinical outcomes, the main hypothesis of this thesis was whether a FL-centred hub and spoke model for the provision of high volume cataract surgery would be significantly more productive than an equivalent attempt at a high-volume CPS service. This translated into a statistically significant improvement of one extra case per OR. However, this was insignificant in terms of reducing costs, and indeed the FL service was £145 more expensive per case. Based on the results in chapter 2, in terms of productivity it can be easily suggested that this money would be more efficiently used in recruiting additional AHPs to support the surgeon by undertaking non-surgical tasks during theatre lists. The findings of this study are important in that it was possible to extrapolate that, with our timings, one FL could support up to 4 ORs which would be relevant for an organisation planning to design such a high-volume hub and spoke system.

Finally, FS-AKs had not previously been compared to LRIs in their efficacy at reducing corneal astigmatism. Approximately 25% of the cases treated in the RCT had corneal astigmatism >0.9D and they were offered LRI or FS-AK appropriately. Analysis by the Alpins method was performed which showed a significantly lower DV and greater CI in the FS-AK group(H. W. Roberts MSc FRCOphth et al., 2018). The IOS was of near significance. This is an important finding, where it appears that the precision and automation of the FL can demonstrate superiority over a manual approach to corneal relaxing incisions. In addition to the refractive results, as the FS-AKs do not penetrate the epithelium they likely to be safer and more comfortable in the post-operative period, although we did not test for this in our study. As FL-dissected flaps have largely superseded the microkeratome in LASIK, the FS-AK similarly may become the preferred technique for the correction of low to moderate astigmatism, where available.

8.2. Future direction of study

Regardless of any further studies relating to the FL, the results of this thesis strongly support the need for further research on OR productivity to understand how the NHS can improve efficiency in this service. It is striking that the Monitor report called for a 20% improvement in efficiency in elective ophthalmic and orthopaedic surgery, yet a simplistic view of the results in chapter 2 suggest that a 100% improvement in theatre output is possible (Monitor, 2015a). It is of note that chapter 2 represents the first published study to perform cataract surgery TMS, focussing on the role of every team member and not just the effects of surgical time on theatre productivity (H. W. Roberts MSc FRCOphth, Myerscough, et al., 2017). The intention of the TMS was not to highlight to NHS managers the under-utilisation of cataract theatres but to provoke a discussion, the heart of which is how best to incentivise the whole surgical team. By conducting an RCT, the number of patients treated on a CPS list increased from an average of 5.4 at St Thomas' to 8 (with 3 AHPs), and after the study concluded, promptly fell to original levels. Improving efficiency within cataract services could save the NHS hundreds of millions of pounds.

One limitation of the FLACS RCT was the limited duration of the follow up to 4 weeks. Two reasons for the choice of 4 weeks were that this is a common point to review patients after cataract surgery and is a common time point at which results are reported in the literature. Also, I would not have been able to include longer follow up within the time span of this MD. We are currently collecting the 12-month outcomes from the FLACS study to look for longer term outcomes such as for lens decentration, PCO rates and the stability of the LRIs and FS-AKs.

Planning of health policy of new technology or techniques requires calculation of the ICER. This would allow the financial quantification of any clinical benefit from FLACS. I suggest that a meta-analysis of UK based studies be conducted to allow for organisations such as NICE to determine healthcare policy for FL into the future.

Whilst the studies within my thesis demonstrated that FLACS technology was both non-cost effective and did not offer any clear clinical benefits over CPS, it should be remembered that this technology has only been in clinical practice for cataract surgery for the past decade and is still in its infancy. It is important to remember that this technology represents the first step in the automation of this very commonly performed procedure and technology will continue to improve. The eye, by virtue of its accessibility and transparency of the cornea and internal structures, lends itself to the development of automation and robotics to undertake such delicate surgical procedures as cataract surgery and intraocular lens insertion. Indeed, robotics are already being employed in retinal surgery within a research context (Uneri et al., 2010). The development of faster FL lasers with lower energies and smaller but more numerous cavitation bubble creation, may allow for the emulsification of lens nuclear material rather than its fragmentation. This combined with faster, real time OCT scanning and precise robotic arm manipulations may, even within the next 10-20 years allow, for the complete automation of the cataract surgery process, with improved surgical precision and safety and perhaps even without the need for surgeon and 24-hour utilization of the OR. The introduction of FLACS perhaps represents the first step in this “brave new world” for Ophthalmology and whilst not cost-effective or clinically beneficial at present does merit further attempts at refinement.

Chapter 9. Abbreviations in the Text

ACD	Anterior Chamber Depth
AHP	Allied Health Professional
ANOVA	Analysis of Variance
A of E	Angle of Error
BCE	Before Common Era
CCC	Continuous Curvilinear Capsulorrhexis
CCI	Clear Corneal Incision
CCT	Central Corneal Thickness
CDE	Cumulative Dissipated [phacoemulsification] Energy
CDVA	Corrected Distance Visual Acuity
CE	Conformité Européene
CFT	Central Foveal Thickness
CI	Correction Index
CSMO	Clinically Significant Macular Oedema
CPS	Conventional Phacoemulsification Surgery
CUSUM	Cumulative Sum Method
D	Dioptres
DM	Descemet's Membrane
DV	Difference Vector
ECL	Endothelial Cell Loss
ELP	Effective Lens Position
EPT	Effective Phacoemulsification Time
FL	Femtosecond Laser
FS-AK	Femtosecond Laser Arcuate Keratotomy
FLACS	Femtosecond Laser Assisted Cataract Surgery
GA	General Anaesthetic
I/A	Irrigation Aspiration
ICER	Incremental Cost Effectiveness Ratio
IFIS	Intraoperative Floppy Iris Syndrome
IOL	Intraocular Lens
IOP	Intraocular Pressure
IOS	Index of Success
logMAR	Logarithm of Minimal Angle of Resolution

LRI	Limbal Relaxing Incision
LS	Laser suite
nAMD	Neovascular Age Related Macular Degeneration
NHS	National Health Service
NICE	National Institute for Health and Care Excellence
NIHR	National Institute for Health Research
nm	nanometer
NOD	National Ophthalmic Database
N.S.	Non significant
OCT	Optical Coherence Tomography
ODCU	Ophthalmic Day Care Unit
ON	Ophthalmic Nurse
OR	Operating Room
OT	Ophthalmic Technician
PBK	Pseudophakic Bullous Keratopathy
PCO	Posterior Capsular Opacification
PCR	Posterior Capsular Rupture
PHVA	Pinhole Visual Acuity
PI	Patient Interfaces
PMMA	Polymethylmethacrylate
PROM	Patient Reported Outcome Measure
QALY	Quality Adjusted Life Year
RCOphth	Royal College of Ophthalmologists
RCT	Randomised Controlled Trial
SD	Standard Deviation
SEM	Scanning Electron Microscopy
SIA	Surgically Induced Astigmatism
TIA	Target Induced Astigmatism
TMS	Time Motion Study
TN	Theatre Nurse
UDVA	Unaided Distance Visual Acuity
WHO	Word Health Organisation

Chapter 10. References

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Chapter 11. List of figures and tables within the text

Chapter 12. Supplementary material

12.1. Roberts, H., Myerscough, J., Borsci, S., Ni, M., & O'Brart, D. P. S. (2017). Time and motion studies of National Health Service cataract theatre lists to determine strategies to improve efficiency. British Journal of Ophthalmology,

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Time and motion studies of National Health Service cataract theatre lists to determine strategies to improve efficiency

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ABSTRACT

Aim To provide a quantitative assessment of cataract theatre lists focusing on productivity and staffing levels/tasks using time and motion studies.

Methods National Health Service (NHS) cataract theatre lists were prospectively observed in five different institutions (four NHS hospitals and one private hospital). Individual tasks and their timings of every member of staff were recorded. Multiple linear regression analyses were performed to investigate possible associations between individual timings and tasks.

Results 140 operations were studied over 18 theatre sessions. The median number of scheduled cataract operations was 7 (range: 5–14). The average duration of an operation was 10.3 min±(SD 4.11 min). The average time to complete one case including patient turnaround was 19.97 min (SD 8.77 min). The proportion of the surgeons' time occupied on total duties or operating ranged from 65.2% to 76.1% and from 42.4% to 56.7%, respectively. The correlations of the surgical time to patient time in theatre was R^2=0.95. A multiple linear regression model found a significant association (F(3,111)=32.86, P<0.001) with R^2=0.47 between the duration of one operation and the number of allied healthcare professionals (AHPs), the number of AHP key tasks and the time taken to perform these key tasks by the AHPs.

Conclusions Significant variability in the number of cases performed and the efficiency of patient flow were found between different institutions. Time and motion studies identified requirements for high-volume models and factors relating to performance. Supporting the surgeon with sufficient AHPs and tasks performed by AHPs could improve surgical efficiency up to approximately double productivity over conventional theatre models.

INTRODUCTION

In 2014–2015, over 370 000 cataract operations were performed by the National Health Service (NHS) in the UK.[1] This was 3.7 times the number performed in 1989, with cataract surgery being the most common operation undertaken in the UK.[2] The demand for cataract surgery is expected to rise still further with increasing life expectancy, rising population size, growing patient expectations and an increase in age-related chronic diseases associated with cataracts, such as diabetes.[3] Surgeons are also conducting, and patients are being referred and presenting for, cataract surgery at an earlier stage of the disease.[4] In 1990, less than 9% of eyes which underwent cataract surgery had a Snellen acuity of 6/12 or better,[4] while two decades later in the period between August 2006 and November 2010, the Royal College of Ophthalmologists' (RCOphth) National Ophthalmology Database showed that 3%, 5% and 36% of eyes undergoing cataract surgery had preoperative Snellen visual acuities of better than or equal to 6/6, 6/9 and 6/12, respectively.[5]

With current financial constraints, the increased future demand for cataract surgery within the NHS is liable to be problematic. Meeting an ever-greater demand with a constrained budget requires an improvement in efficiency while, ensuring that standards of patient care are maintained or improved. A recent report from Monitor (Department of Health) estimated that 13%–20% productivity gains might be made in elective ophthalmology if practices were optimised.[6] The recently published *The Way Forwards* report (RCOphth) found a median of seven cases scheduled per theatre list (range 4–12).[7] To the authors' collective experience, NHS cataract lists exist with anything between 5 and 15 patients routinely booked. Why this difference of a threefold difference in productivity between minimum and maximum values exists in public sector cataract surgery has not received the due attention it should.

In 1911, F.W. Taylor introduced the time and motion study (TMS) as an application of the scientific method to the management of workers in order to improve productivity. Historically, TMS was applied to the manufacturing industry. However, it has also been shown to have useful applications within healthcare.[8 9] A century after the introduction of scientific management method, there is genuine interest in aggregating knowledge in healthcare workflow, inefficiencies, patient safety and quality. Among several approaches commonly used to date, TMS, which involves continuous and independent observation of clinicians' work, is generally regarded as a more reliable methodology compared with alternative approaches such as work sampling and time efficiency questionnaires.[8 9]

To provide a quantitative assessment of the efficiency of cataract surgery across several UK hospitals, we conducted TMS investigations at several different institutions and settings. These included weekend waiting list initiative sessions, the provision of NHS cataract surgery in the private sector, as well as routine cataract surgery lists in NHS hospitals. In particular, we focused on surgical time,

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Table 1 Details of cataract theatre lists studied

Institution	1	2	3	4	5
Type of theatre list studied	Routine theatre list	Routine theatre list	A. Routine theatre list B. Weekend initiative list C. Dedicated high volume list	Routine theatre list	NHS patients receiving surgery at adjacent private institution
No of sessions observed	4	4	A. 2 B. 2 C. 2	2	2
Median no of operations scheduled/list	6	6	A. 7.5 B. 9 C. 13.5	7	13
Total no of cases studied	23	22	A. 14 B. 16 C. 27	12	26
Percentage of operations cancelled on the day (%)	4.2%	8.3%	A. 6.67% B. 11.1% C. 0	14.3%	0
Allied healthcare professionals	3 nurses	3 nurses, 1 HCA	A. 3.5 nurses, 1 ODP B. 3 nurses, 1 HCA C. 4 nurses, 1 HCA, 1 ODP, 1 medical secretary	3 nurses	2 nurses, 1 HCA, 1 ODP

HCA, healthcare care assistant; NHS, National Health Service; ODP, operating department practitioner.

surgeon tasks within and outside theatre, patient throughput, staffing levels of allied healthcare professionals (AHPs) and their key tasks and timings. By analysing these variables and investigating correlations between them, we hope to provide greater awareness of different models of practice, to identify important factors leading to differences in the individual number of cataract operations per theatre session and provide information to improve surgical productivity while maintaining high levels of patient safety. To the authors' knowledge, there are no previous examples of such TMS investigations of cataract surgery with a public health setting in the literature.

METHODS

Continuous observation TMS of 18 routine 4-hour cataract theatre sessions, was undertaken in five different hospitals and settings. These settings included two district general hospitals, two teaching hospitals, a weekend waiting list initiative theatre session in an NHS hospital, a dedicated high-volume theatre list in an NHS hospital and an NHS cataract surgery list in a private hospital (table 1). The five institutions studied were the BMI Southend Private Hospital, Norfolk and Norwich NHS Foundation Trust, Guy's and St Thomas' NHS Foundation Trust, Southend University Hospital NHS Foundation Trust and West Suffolk NHS Foundation Trust. A consultant ophthalmic surgeon or associate specialist performed all lists, no lists were designated teaching lists. All patients were listed for only routine cataract surgery and all surgeries were conducted by phacoemulsification with intraocular lens insertion under local anaesthesia. All cases were unilateral. The number and type of AHPs supporting each individual theatre list was recorded (table 1).

Each list had been observed prior to undergoing TMS investigation in order to identify preliminary staffing models and tasks (tables 1 and 2). Agreement analysis was used to define the list of tasks and then a basic model for each setting was set up and used as a template to observe and time the steps of every defined task (table 2). Each list was observed by one or two ophthalmologists (HWR and JM). Each observer used a template Excel spreadsheet (Microsoft, Redmond, Washington, USA) with specifically designed macros to facilitate the prompt and accurate recording of tasks and their timings.

Noting the start and finish times of some of the key tasks was self-explanatory, while other tasks required specific moments agreed on in advance in order to maintain reproducibility. Surgical start and end times were regarded at the point of insertion or removal of lid speculum. Patient entry time was defined as the time from patient entry into theatre until final positioning for surgery had been achieved. Patient exit time was defined as the time from removal of lid speculum to patient exiting the theatre. Start and end of scrubbing were regarded as the opening of the tap and finishing the gowning process. The start and end of the safety checklist were recorded once the first member of staff began speaking until the last member of staff had finished speaking. The start of the scrub nurse clearing up from the case was the time when the first instrument was passed out or dismantled once the lid speculum had been removed. The end of clearing time was recorded once the scrub nurse re-entered the theatre from the sluice, having disposed of all equipment and waste. The cause and duration of any unexpected delays more than 5 min were recorded.

In addition to defining each key task and its reproducible start and finish, a series of quotients were defined as follows and produced for each setting. The efficiency quotient was defined as the proportion of time that the surgeon was engaged in a task (total surgeon time spent productive/total time).[10] The surgery quotient was defined as the proportion of time that surgery was occurring (total surgical time/total time). The theatre utilisation quotient was defined as the utilisation of the maximum available theatre time (time between start of first and end of last case/4 hours).[11]

STATISTICS

Data are presented as non-parametric and parametric as appropriate. Differences between the groups were analysed with one-way analysis of variance (ANOVA) test where appropriate. Linear regression models were calculated to estimate the key factors affecting the time to perform the surgery, and the time

Table 2 Task durations in minutes from common tasks across the institutions studied

Institution	1	2	3A	3B	3C	4	5
Average time of surgery used per session (range)	172.7 (160.03, 180.1)	160.97 (142.61, 176.7)	169.23 (163.87, 174.6)	163.13 (142.7, 182.57)	198.5 (185, 212.3)	122.35 (110.53, 134.17)	210.92 (194.5, 247.33)
Theatre utilisation quotient	71.7%	67.1%	70.4%	67.9%	82.7%	50.8%	87.9%
Theatre utilisation quotient (assuming no cancellations)	74.8%	73.2%	75.4%	76.4%	82.7%	59.3%	87.9%
Efficiency quotient	66.0%	65.2%	66.4%	71.9%	76.1%	65.6%	75.8%
Surgery quotient	53.2%	42.4%	44.0%	42.9%	52.9%	56.1%	56.7%
Average patient time in theatre (SD)	26.74 (5.13)	22.27 (5.1)	17.23 (2.77)	12.84 (2.32)	11.88 (1.4)	19.16 (4.96)	10.06 (4.13)
Average time between cases (SD)	3.75 (1.98)	7.1 (3.67)	6.17 (2.43)	4.9 (56)	1.53 (0.7)	1.4 (1.12)	3.4 (1.4)
Average time from patient entering theatre to start of operation (SD)	8.65 (3.12)	6.67 (2.72)	2.86 (1.18)	2.87 (0.58)	2.45 (2.2)	5.25 (1.98)	1.43 (0.88)
Average time for patient to exit theatre after operation (SD)	2.1 (1.1)	3.2 (1.03)	2.05 (0.65)	1.93 (0.4)	1.25 (0.3)	2.53 (1.03)	1.08 (0.48)
Average surgical time (SD)	15.98 (3.93)	12.4 (2.8)	10.63 (2.53)	8.1 (0.6)	7.43 (1.47)	11.43 (2.61)	7.55 (3.38)
Average time surgeon spends on paperwork (SD)	0.87 (0.37)	3.7 (1.45)	1.85 (0.93)	1.88 (0.62	0	0	0.95 (0.42)
Average surgeon scrub time (SD)	2.33 (0.75)	2.32 (1.1)	1.92 (0.57)	1.98 (0.78)	1.43 (0.4)	1.43 (0.37)	1.6 (0.53)
Average nurse scrub time (SD)	2.4 (0.8)	2.13 (0.7)	3.77 (1.28)	2.85 (0.97)	2.95 (0.33)	2.4 (1.07)	1.47 (0.8)
Average nurse time to prepare scrub trolley (SD)	4.98 (1.55)	4.1 (1.4)	7.95 (0.88)	8.03 (1.72)	7.17 (1.5)	5.6 (1.9)	5.27 (1.53)
Average nurse time to prepare phacoemulsification machine (SD)	2.72 (2.72)	4.18 (1.8)	3.15 (1.05)	2.82 (0.65)	2.6 (0.65)	3.9 (1.37)	2.07 (0.8)
Average nurse time to clear equipment (SD)	3.68 (0.68)	3.48 (1.07)	5.35 (1.53)	4.93 (1.47)	6.37 (1.03)	7.5 (2.08)	3.48 (2.07)
Average time spent on WHO checklist (SD)	0.65 (0.27)	0.67 (0.17)	0.7 (0.27)	0.45 (0.15)	0.27 (0.1)	0.52 (0.18)	0.73 (1.08)
Total no of key tasks performed by AHP per case	11	11	12	12	15	12	18
Average time taken to complete key tasks by AHP per case (SD)	9.95 (6.56)	19.9 (4.15)	26.57 (2.3)	26.3 (3.15)	29.67 (3.44)	29.43 (4.89)	28.7 (6.1)
Average scheduled team break time	Nurses-staggered break, no break for surgeon	Nurses-staggered break, no break for surgeon	14.72	18.2	20.5	No breaks (relatively short theatre session)	37.8

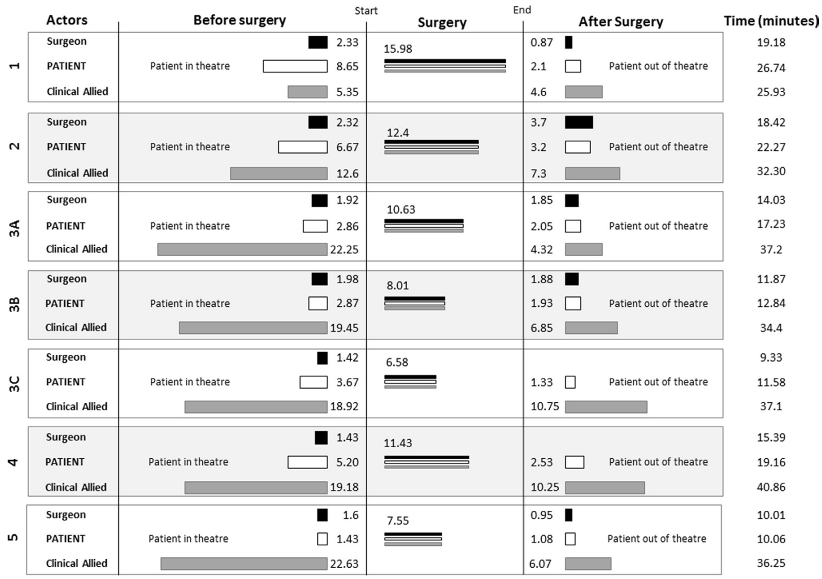

Figure 1 Diagram of model summarising the results of the time motion studies.

an individual patient spent in theatre. Descriptive statistics was used to calculate averages and SD of the performances in each list. IBM SPSS Statistics for Windows (V.22.0, IBM) was used to perform the analysis.

RESULTS

TMS of 140 individual cataract operations were prospectively recorded during 18 NHS cataract theatre sessions. All cataract operations were performed with phacoemulsification. All operations were under local anaesthesia. All operations were unilateral. No operations were combined procedures or required additional procedures outside small-incision phacoemulsification cataract extraction and intraocular lens insertion. The details of each theatre session can be seen in table 1.

Timings from each theatre list can be seen in table 2 and figure 1. The reason and duration of any unscheduled delays can be seen in table 3. Mapping of the workflow of the two highest-volume theatre lists can be seen in figures 2 and 3.

The median number of operations per 4-hour theatre session was 7 (range 5–14). The mean time to perform a cataract operation was 10.3 min (SD 4.11 min). The mean time to complete one case including patient turnaround was 19.97 min (SD 8.77 min). The mean surgical scrub time was 1.86 min (SD 0.77 min).

Table 3 The reason and duration, in minutes, of any unscheduled delays

Institution 1		Institution 2		Institution 3B		Institution 5	
Reason for delay	**Time**	**Reason for delay**	**Time**	**Reason for delay**	**Time**	**Reason for delay**	**Time**
Waiting for next patient from day case unit	5.88	Instrument error	6.52	Patient vasovagal episode	10.3	Waiting for next patient from day case unit	6.0
Surgeon examining staggered patients	9.5	Equipment error	5.17			Waiting for next patient from day case unit	5.75
Waiting for next instrument trolley to be ready	7.43	Surgeon required to see patient in clinic	13.23				
Surgeon out of theatre	8.75	Surgeon late for theatre due to clinic overrun	28.17				
Surgeon examining staggered patients	08.32	Surgeon reviewing latecomer	7.35				
		Waiting for next patient from day case unit	10.5				
		Waiting for next patient from day case unit	8.95				
Total	39.88		79.88		10.3		11.75

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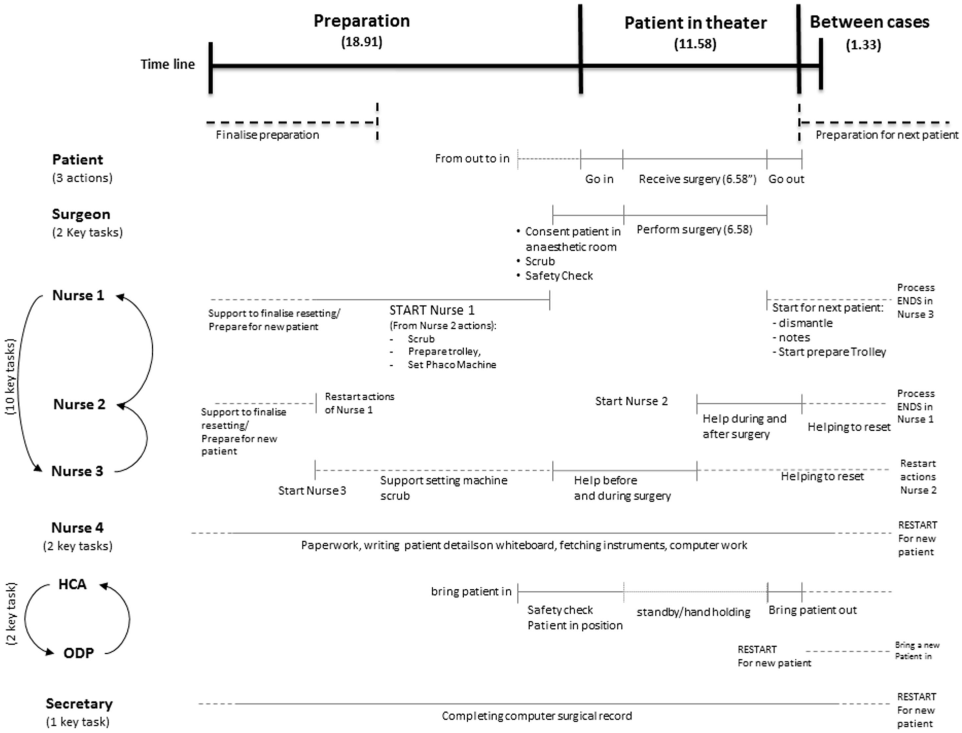

Figure 2 Model of workflow of staff duties at institution 3C. HCA, healthcare assistant; ODP, operating department practitioner.

The mean time to complete preprocedure WHO checklist was 0.55 min (SD 0.52 min). The mean time to complete postprocedure paper/computer work was 1.77 min (SD 1.35 min). The mean time for patients to enter theatre to being positioned for surgery was 2.28 min (SD 1.88 min). The mean time from patient entry to start of operating was 4.56 min (SD 1.49 min). The mean time for patient to exit theatre from removal of lid speculum was 1.90 min (SD 1.00 min). The mean duration of patients' time in theatre was 17.07 min (SD 7.30 min). The mean time in between cases was 4.12 min (SD 2.78 min). The correlations of the surgical time to patient time in theatre was $R^2=0.95$. The correlation between surgical time and number of cases scheduled was $R^2=0.696$.

The minimum number of AHPs (nurses/healthcare assistants/ operating department practitioners) allocated to a theatre list in this study was 3. The majority of AHPs in this study were registered nurses. The two theatre lists with the greatest number of cases scheduled had either 4 or 7 AHPs (table 4). There was a moderate correlation between number of AHP and number of cases scheduled ($R^2=0.489$). If only the public healthcare settings were included (institutions 1, 2, 3A–C and 4) and we excluded the one private institution under taking NHS operations (institution 5), where practices may differ from the NHS, the correlation between number of AHP and number of cases scheduled was much higher ($R^2=0.823$). However, if we excluded the institution with the highest number of AHP per case (3C) from the analysis, the correlation became insignificant ($R^2=0.13$).

Multiple linear regression models

A multiple linear regression model was calculated to predict the time to perform one operation based on three factors: (1) the number of AHPs, (2) the number of key tasks performed by AHPs and (3) time taken to perform these key tasks by AHPs. A significant regression was found ($F(3,111)=32.86, P<0.001$) with an R^2 of 0.47. All the three factors were significant predictors of the time to perform a surgery. In particular, the surgical time decreases by 0.95 min for each additional AHP involved, by 0.39 min for every additional task performed by AHP and by 0.19 min for each additional minute spent by AHP performing tasks.

A one-way ANOVA way was performed to control for the effect on surgical time by: (1) the number of AHPs, (2) the number of key tasks performed by AHPs and (3) time taken to perform these key tasks by AHPs. There was a significant effect ($P<0.001$) of all the factors as follows: (1) $F(1,113)=35.12$, $P=0.001$), (2) $F(1,113)=53.43$, $P=0.001$) and (3) $F(1,113)=42.23$, $P=0.001$) (figure 4).

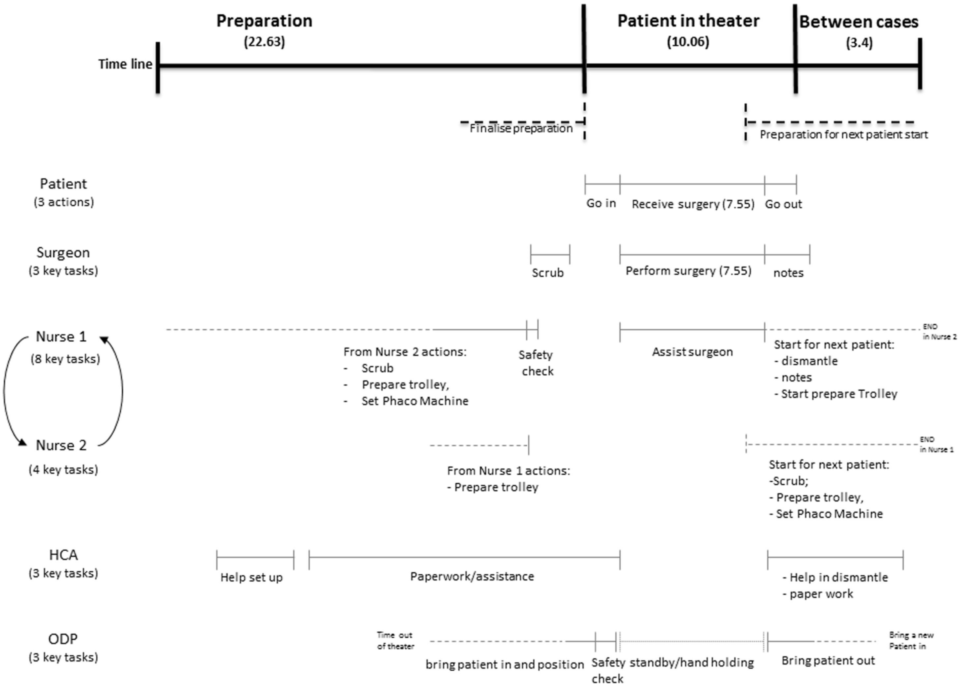

Figure 3 Model of workflow of staff duties at institution 5. HCA, healthcare assistant; ODP, operating department practitioner.

A similar multiple linear regression model was calculated to predict the effect of the same three factors: (1) the number of AHPs, (2) the number of key tasks performed by AHPs and (3) time taken to perform these key tasks by AHPs on the total patient time in theatre. Factors (2) and (3) were significant predictors of the time an individual patient spent in theatre, that is, the total time to complete one surgical case. The model was significant ($F(2,116)=43.18, P<0.001$) with an R^2 of 0.43. The length of patient time in theatre decreased by 0.76 min for each task performed by AHPs and by 0.19 min for each minute spent by AHPs to perform their tasks.

A one-way ANOVA was performed to control the effect on the total patient time in theatre by: (1) the number of AHPs, (2) the number of key tasks performed by AHPs and (3) time taken to perform these key tasks by AHPs. There were significant effects of factors 2 and 3 ($F(1,117)=43.97, P<0.001$) (figure 4).

Table 4 Staffing levels associated with number of cases scheduled

Setting	No of allied health professionals	Median no of cataracts scheduled/session
1	3	6
4	3	7
2	4	6
3A	4.5	7.5
3B	4	9
5	4	13
3C	7	13.5

DISCUSSION

This study adopted a TMS approach to evaluate the efficiency of public sector cataract surgery in the UK. We observed a significant variance in the running of cataract theatre lists at five different UK institutions, the most striking of which is the number of patients scheduled per list, which ranged from medians of 6–13.5. From the perspective of the public healthcare sector, it is imperative to maximise the efficiency of elective surgery while maintaining quality and safety.[6] The average duration of a cataract operation was 10.3 min and the total time including preprocedure and postprocedure preparation and patient turnaround was 19.97 min. It could be expected, therefore, that at least 12 operations could be completed in a 4-hour session and yet the median number of cases booked to a theatre list of 7 is much less. On the basis of the results of this TMS, one could expect that an increase in 70% efficiency might be possible. Whether this is an achievable target and why it is not currently being realised is a matter of conjecture, but certainly it highlights the great need to identify possible factors necessary to improve the efficiency of NHS cataract surgery.

It was interesting to document that the sessions (institutions 3C and 5) providing the highest median number of cases per list (13, 13.5) and highest theatre utilisation and efficiency quotients, had the longest duration of staff breaks, suggesting

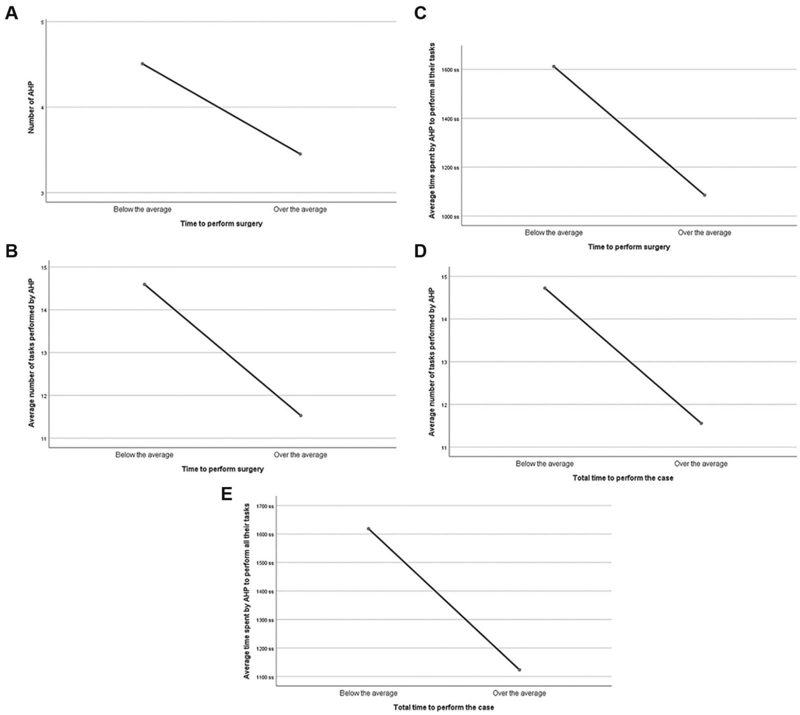

Figure 4 The significant relationships identified by analysis of variance. The average time to perform the surgery was equal to 10.25. The average time to perform the case was equal to 14.08. (A) The relationship between the time to perform the surgery and number of allied healthcare professionals (AHPs). (B) The relationship between the time to perform the surgery and number of tasks performed by AHPs. (C) The relationship between the time to perform the surgery and the time spent by AHPs to perform their tasks. (D) The relationship between the time to perform the case and number of AHPs. (E) The relationship between the time to perform the case and the time spent by AHPs to perform their tasks.

that these units have discovered how to 'work smarter, not harder' (table 2, figures 1–3). This strongly suggests that by changing working practices efficiency can be improved without increasing individual staff workload.

This assumption is supported by the observation that institutions 4 and 5 share the same population, yet there are noticeable differences between the TMS of their theatre sessions, especially in terms of median number of cases per list (7 vs 13), theatre utilisation quotient (50.8% vs 87.9%) and efficiency quotient (65.6% vs 75.8%) (table 2). As patient demographics should be similar at these two settings, differences in practice and efficiency presumably arise from internal organisation of the cataract theatre lists rather than external factors.

In considering the TMS of the surgeons, it is important to recognise that the theatre session is not an independent entity. Rather, differences in theatre practices often stemmed from factors outside the theatre itself, such as in the day case ward/clinic. For example, at institutions 1 and 4, the surgeons performed slit-lamp examination and marked all patients on the day of surgery, at institution 2 the surgeon met the patients and marked them, at 3A/B/C the surgeon met the patient, marked and consented them, while at 5 (which had the highest theatre utilisation quotient and second highest median number of cases at 13) all such tasks were performed by staff on the day-case unit. This suggests that using AHPs to undertake some of the duties of the surgeon outside theatre, might be an important factor in improving efficiency by ensuring that the surgeon spends as much in theatre as possible during each allocated 4-hour cataract surgery session. This is supported by the observation that institution 1 (with a joint lowest median number of cases of 6 and an efficiency quotient of only 66%) was the only unit in which there was staggered patient arrival and surgeon performing preoperative examination, leading to a time relating to these duties of 26.57 min out of theatre during the 4-hour sessions (tables 2 and 3). Similarly, at institution 2 (joint lowest median number of cases of 6 and efficient quotient of 65.2%), the surgeons spent 48.75 min outside the operating theatre due to outpatient clinic over-run and the need to see patients on the day case ward (figure 1, tables 2 and 3). Clearly to achieve optimum efficiency it is imperative for the surgeon to be available within theatre to undertake the surgery rather than performing duties outside. Whether this best achieved by AHPs performing such outside duties instead of the surgeon as at institution 5, or ring fenced time before the theatre session itself is a matter of conjecture.

Some units allowed patients to arrive on a staggered basis for their convenience and reduced overall patient waiting time (institutions 1, 3A/B/C, 5), while the remainder requested that all patients were present for the pretheatre ward round. As such practices did not affect the overall median number of cases or efficiency quotients (table 2), it seems a reasonable approach to stagger arrival times for patient convenience, provided protocols are introduced to avoid surgeons spending time out of theatre, as at institution 5.

Based on our observation, a minimum of four AHPs appear to be required to provide a high-volume service. This criterion was met at all settings other than institutions 1 and 4 (table 4). Increasing the number of cases towards the goal of high-volume lists may require either/both an increase in the number of AHPs supporting the surgeon with additional tasks (as in setting 3C) or changes in working practice (as in setting 5), with four AHPs performing more supporting tasks. It is our experience that in addition to the scrub nurse and circulating AHP, at least two AHPs are required to be able to clear up from the previous case and, more importantly, prepare for the subsequent case so there is only a minimal wait between cases. This is achieved at institutions 3C and 5 (this lists with the highest volumes of patients treated per session) with 18.92 and 22.63 min of AHP preparation time, respectively, before the patient even enters theatre (figures 2 and 3). Ideally, the gap between cases needs to be minimised to the time it takes to escort the patient out and in, perform WHO checklist, and for the surgeon to rescrub. In this series, the length of time from the end of one case to the start of the next ranged from 5.92 to 16.8 min.

Between the institutions the average surgical time varied from 7.43 to 15.98 min. This variation may reflect different case mix or differences between surgeons with some being faster/more experienced than others. The surgeons in lists 3C and 5 have a national reputation of excellence and are known for their expertise and surgical skills and this may have created outlying results. However, despite this the correlation between AHP numbers and tasks was strong and means that efficiency can be improved for those that do not have exceptional surgical skills. The correlation between surgical time and number of cases scheduled was $R^2=0.696$, suggesting that factors such as surgical experience and case mix are likely to have a part to play in cataract surgery efficiency. However, we found significant correlation between the time undertaken to perform cataract surgery and the number of AHPs, the number of key tasks performed by AHPs and the time taken to perform these key tasks by AHPs ($P<0.001$). This was confirmed by one-way ANOVA testing, suggesting that alteration of the number of AHPs supporting a cataract surgery list and surgeon, their duties and their total time performing tasks, is strongly associated with and can indeed influence the time to perform individual cataract surgery (figure 4). Similarly, a strong correlation, confirmed by one-way ANOVA- testing, was found between the number of key tasks performed by AHPs and the time taken to perform these key tasks by AHPs on the total patient time in theatre ($P<0.001$). Such correlations appear to highlight the importance of AHPs and their designated tasks in the development of high-volume NHS cataract surgery.

Concerning institution 5, which appeared to be an outlier in terms of correlation of number of AHPs with efficiency, these results might be explained by the fact that this was a private institution with different working practices from public health sector settings and there were direct financial incentives for the numbers of patients treated which it could be assumed positively influence productivity. Most importantly, while the number of AHPs supporting the cataract theatre list at institution 5 was 4, the number of key tasks performed by AHPs per case was much higher at 18 than any other organisation (table 2). At site 5, it clearly appeared that AHPs were undertaking many of the tasks performed by the surgeons at other institutions, which ensured that the surgeon was spending far more time in theatre undertaking surgery than at any other institution. As such, this unit could optimise surgical productivity and theatre utilisation. Indeed the results at institution 5 strongly support our correlations concerning the importance of AHPs, their roles and tasks they undertake, in optimising cataract surgical list efficiency. It appears that expansion of the role of AHPs in the public sector health setting to incorporate some the non-surgical roles currently undertaken by the surgeon, as well as the maintenance of adequate AHP staffing levels is vital to optimise cataract surgery efficiency.

There was generally an under utilisation of the full 4-hour (240 min) theatre session. Average theatre utilisation was 70.11% (range 50.8%–87.9%) and was 73.9% (range 59.3%–87.9%) when extrapolated to take into account the cancelled operations. The reasons for delayed start of theatre sessions included the surgeon being delayed by an overbooked clinic or administrative duties on the day case ward (table 3). Preoperative examination of surgical patients and associated duties (patient marking, confirmation of consent, etc) is an integral part of the surgical process, but duration should be minimised to maximise potential surgical time. However, in the interests of patient safety, it is not suggested that the target for theatre utilisation should be 100% due to the possibility of a case taking longer than expected or the event of a surgical complication, although the risks of surgical complications in cataract surgery is generally low (<5%).[5]

This study does have a number of limitations. First, it focused on single independent consultant or associate specialist surgeon theatre sessions and not on training lists with junior doctors. Clearly, there is a need to balance the desire for high-volume services and the promotion of high-quality provision of training for the next generation of surgeons. However, if sufficient high volume can be achieved in single surgeon lists, then we believe this can reduce the pressure of service provision in lists with junior trainees. Indeed, given the increased future demand for cataract surgery within the NHS (as discussed above), there is a great need for senior trainees as future consultant surgeons to have exposure to high-volume models of cataract surgery.

Second observations were made based on a relatively small number of observed sessions (18). To our knowledge, this is the first TMS of its kind in cataract surgery. TMS are, by their nature, very labour intensive. Historically, TMS would often require one observer for each person studied which would, of course, introduce great difficulty (logistical and financial) in studying a cataract theatre session. However, we have found that through the use of Macros on Microsoft Excel, we were able to record timings for all staff involved with a theatre session with no more than two observers. This would be the first example of TMS of cataract theatre sessions published, which we feel is of great importance, especially in understanding differences in productivity within state-funded healthcare systems. Clearly, however, there is scope for future research incorporating greater numbers of operations at more institutions which may facilitate analysis of a greater number of factors and less risk of chance findings.

It is also of note that the five hospitals participating in this study incorporated a mixture of academic centres and district general hospitals, with both rural and urban populations. They were chosen carefully to reflect a broad spectrum of environments. However, this study does not claim to represent universal provision of cataract services across the UK. We did not evaluate every model of surgical provision, including patients having surgery under sedation or general anaesthetic (GA). However, the vast majority of cataract surgery performed with the UK is undertaken under topical/local anaesthesia[1 5] and the aim of this study was to focus on the delivery of high-volume services, wherein GA cases are unlikely to feature. Furthermore, it was assumed that all theatre teams were experienced with cataract theatre lists and familiar with working with each other. Indeed during the course of the TMS nothing was observed to the contrary.

Finally, although the focus of this study was the efficiency of cataract surgery, the metrics of the quality of the surgery, such postoperative visual acuity, postoperative complications, postoperative refraction and patient satisfaction were not evaluated. It is important to remember that the quality of any aspect of cataract surgery and overall patient satisfaction should never be compromised to enhance efficiency. To further investigate this, we are currently investigating patient satisfaction and patient-reported outcomes in high-volume cataract models.

CONCLUSION

This current TMS study highlights the huge variation in the efficiency of cataract surgery within the NHS. It suggests that, with provision of sufficient levels of AHP staffing and expansion of the roles of AHPs , productivity in cataract surgery and theatre utilisation could be significantly improved in the public sector.

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Time and motion studies of National Health Service cataract theatre lists to determine strategies to improve efficiency

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Financial modelling of femtosecond laser-assisted cataract surgery within the National Health Service using a 'hub and spoke' model for the delivery of high-volume cataract surgery

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ABSTRACT

Aims: To develop financial models which offset additional costs associated with femtosecond laser (FL)-assisted cataract surgery (FLACS) against improvements in productivity and to determine important factors relating to its implementation into the National Health Service (NHS).

Methods: FL platforms are expensive, in initial purchase and running costs. The additional costs associated with FL technology might be offset by an increase in surgical efficiency. Using a 'hub and spoke' model to provide high-volume cataract surgery, we designed a financial model, comparing FLACS against conventional phacoemulsification surgery (CPS). The model was populated with averaged financial data from 4 NHS foundation trusts and 4 commercial organisations manufacturing FL platforms. We tested our model with sensitivity and threshold analyses to allow for variations or uncertainties.

Results: The averaged weekly workload for cataract surgery using our hub and spoke model required either 8 or 5.4 theatre sessions with CPS or FLACS, respectively. Despite reduced theatre utilisation, CPS (average £433/case) was still found to be 8.7% cheaper than FLACS (average £502/case). The greatest associated cost of FLACS was the patient interface (PI) (average £135/case). Sensitivity analyses demonstrated that FLACS could be less expensive than CPS, but only if increased efficiency, in terms of cataract procedures per theatre list, increased by over 100%, or if the cost of the PI was reduced by almost 70%.

Conclusions: The financial viability of FLACS within the NHS is currently precluded by the cost of the PI and the lack of knowledge regarding any gains in operational efficiency.

Strengths and limitations of this study

- Data were collected and collated from four NHS foundation trusts of various sizes, locations and demographics to ensure the conclusions could be more representative.
- This is the only study investigating the financial implications of femtosecond laser-assisted cataract surgery (FLACS) which highlights the significance of the cost of the disposable patient interfaces over the capital cost of the laser machine itself.
- This is the only study investigating the financial implications of FLACS which has developed a working model incorporating a laser to improve, rather than impede productivity.
- This study falls short of providing an incremental cost-effectiveness ratio for FLACS. For the purposes of this model, clinical outcomes are assumed to be equivalent. This is currently supported by the latest evidence.

INTRODUCTION

In 2014–2015, over 370 000 cataract operations were performed on the National Health Service (NHS).[1] This was 3.7 times the number performed in 1989.[2] The need for cataract surgery is expected to rise further with increasing life expectancy, rising population size, growing patient expectations and an increase in age-related chronic diseases associated with cataracts, such as diabetes.[3] With current financial constraints, this increased future demand for cataract surgery within the NHS is liable to be problematic.

Femtosecond laser (FL) technology has been recently introduced into cataract surgery in an attempt to automate and improve the efficacy and safety of some of the surgical steps within this procedure.[4] Within the scientific literature, there are now numerous prospective case series supporting its usage and continued development and more surgeons are adopting this new technology.[4–9] However, while FL technology undoubtedly offers great surgical precision, a recent meta-analysis shows no significant advantages in terms of safety and efficacy of FL-assisted cataract surgery (FLACS) over conventional phacoemulsification cataract surgery (CPS).[10] Two large multicentre randomised controlled trials (RCTs) are currently underway in France and the UK and may provide further evidence as to whether there is a difference in the clinical outcomes from FLACS.[11 12]

Until evidence exists of improved surgical outcomes, it is difficult at present to support the widespread implementation of FLACS. This is particularly pertinent as the introduction of FLACS has significant associated financial costs. These include initial purchase costs of the FL system itself, servicing, depreciation and the individual patient interfaces (PI), which call into question its financial viability, especially in a state-funded healthcare system. The majority of existing literature on the economics of FLACS originates from healthcare systems within countries such as the USA or Australia, where additional costs from procedures perceived as having a premium status may be passed onto the patient in the form of a copayment system.[13–15] In these healthcare systems, the existing literature suggests that FLACS is not, at this time, a cost-effective solution. It is not surprising, therefore, that adoption of this technology within the NHS so far has been minimal and largely directed at research rather than service provision.

Despite associated costs, by its very nature, the FL offers the potential to remove several steps of cataract extraction from needing to be performed by a fully trained surgeon in a fully equipped ophthalmic operating theatre. FL technology can automate several surgical steps of the cataract procedure, such as corneal incisions, arcuate keratotomies, capsulotomy and nuclear lens division, all of which can be potentially undertaken with this technology by a doctor in training or suitably trained nurse or technician in a clean room. By reducing the actual amount of time each patient spends within the operating theatre under the care of a trained surgeon, the volume of surgical cases undertaken in a given period of time might potentially be increased. This may be especially true if a 'hub and spoke' model is utilised, with the FL performing these initial automated steps and then allowing the completion of the surgical procedure to be undertaken in more than one operating theatre at a time. If the number of cases per theatre session can be increased sufficiently then the initial expenditure and additional costs associated with FL technology might be offset.

For FLACS to see increased adoption by a state-funded healthcare system such as the NHS, it would need to be shown to be cost-effective based on an acceptable incremental cost-effectiveness ratio (ICER). The ICER is defined by the difference in the cost between two possible interventions divided by the difference in their clinical effectiveness. This study aims to investigate, in the absence of clinical outcomes from large RCTs showing any surgical benefit, the cost of incorporating FLACS into the NHS system in order to determine whether the increased costs of equipment may be offset by an increase in the volume of surgery performed.

METHODS

Financial model

A financial model was designed to compare FLACS against CPS for the provision of cataract surgery within the NHS. The inputs for this model can be seen in table 1. The model was based on data from four separate NHS Foundation Trust Ophthalmology Departments (Guy's and St Thomas' NHS Foundation Trust, Norfolk and Norwich NHS Foundation Trust, Peterborough and Stamford NHS Foundation Trust and West Suffolk NHS Foundation Trust) and four manufacturers of commercially available FL devices (Abbott Medical Optics, Santa Ana, California, USA; Ziemer Ophthalmic Systems AG, Switzerland; Alcon Laboratories, Fort Worth, Texas, USA and Bausch & Lomb, Rochester, New York, USA). The data were collated and averaged to ensure the results were more representative than had just one ophthalmology department or one FL been used.

Values for each input were derived from the following sources.

1. Income for each procedure is reimbursed at the NHS national tariffs for 2014–2015 plus an additional market forces factor.[16 17]
2. Costs were divided into direct labour costs, equipment costs and overheads. Direct labour costs per theatre session were derived from NHS pay scales and midpoint values were chosen. This was then proportioned to the estimated duration of each theatre session.
3. Costs relating to the FL were averaged from those provided by four manufacturers of commercially available FL devices.
4. Costs such as estate, equipment and supplies were averaged from four NHS Foundation Trusts' departmental budgets (2014–2015).
5. Pharmacy and administrative costs were obtained by reviewing the departmental budget at our institution.
6. Baseline values for the number of cases achievable per 4-hour theatre session were given nominal values of 7 cases for CPS and 10 cases for FLACS. These initial values were then tested using sensitivity and threshold analyses.

The model was tested based on two scenarios: FLACS versus CPS based on an average number of seven cases currently performed on a CPS cataract lists and a FLACS delivery model based on a 'hub and spoke' method with one FL in a clean room and operated by a doctor in training preparing patients for two operating theatres running in parallel with their associated surgeons, nursing and technical support staff.

'Hub and spoke' FLACS model

Our theoretical 'hub and spoke' model for FLACS is based on a single FL platform in a clean room and operated by an ophthalmology registrar or suitably trained allied health professional and supported by a theatre nurse (figure 1). The laser would be programmed to perform capsulotomy, nuclear lens division and arcuate keratotomies (when indicated) for each individual patient. Patients would be prepared for two operating theatres running in parallel with their associated surgeons, nursing and technical support staff. The assumed FL treatment time is a maximum of 10 min per patient allowing for the preparation of up to 20 cataract surgery cases, 10 per theatre per 4-hour operating theatre session. The assumed theatre time is a

Table 1 Inputs for the model and nominal values

Source		Input	Value (£)	Range (£)
A				
Income		NHS tariff for cataract surgery	789	729–917
Expenses	Staffing (per session)	Consultant surgeon	246	
		Band 5 nurse	79	
		Registrar/laser technician	101	
		Band 6 nurse/laser technician	102	
		Ward clerk	53	
	Overheads (per year)	Ophthalmic day-case unit	525 620	30 112–1 061 481
		2× operating theatres	585 676	353 245–962 287
	Laser	Initial cost	262 500	175k–350k
		Maintenance/year	28 333	20k–35k
		Cost of patient interface	134.75	99–170
	Other costs	Disposables and IOL (per case)	103	
		Cost of administration, management and pharmacy (per case)	50	
B				
Other variables		Number of cataract operations required per week	55 operations	27–96
		Number of cases on CPS list	7 operations	
		Number of cases on FLACS list*	10 operations	
		Lifetime of FL	10 years	

*Based on the hub and spoke FLACS delivery model.

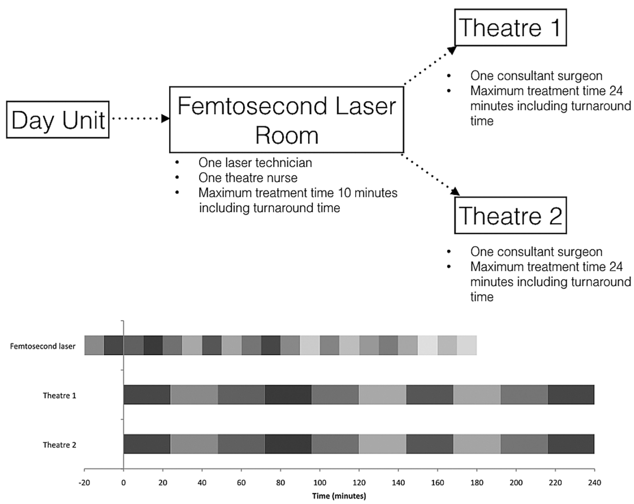

Figure 1 A proposed 'hub and spoke' model for femtosecond laser-assisted cataract surgery.

maximum of 24 min per case. These values are based on our own experience with the FL.

Sensitivity analysis

The model was constructed using Microsoft Excel (Microsoft Corp, Redmond, Washington, USA) based on the range of the above inputs (table 1). Univariate and bivariate sensitivity analyses were conducted by varying the inputs into the model to simulate the impact on the final service costs. The inputs chosen for the sensitivity analysis were as follows:

1. capital cost of the FL,
2. cost of the PI,
3. number of cases possible on a FLACS theatre list,
4. number of cases performed on a CPS list,
5. number of cataract operations required per week.

Threshold analyses were performed on the same variables as the sensitivity analyses to determine threshold values at which FLACS may break even with CPS. The results are reported as weekly costs.

RESULTS

The first model tested FLACS versus CPS based on an average number of seven cases currently performed on CPS cataract lists. Our model estimated that the current CPS service at its existing productivity was costing £433 per case. Using a model that incorporates one FL into one theatre list, and therefore assuming no increase in productivity, the laser increases the cost per case by £167 to £600. Based on these values, the CPS service would be 72% of the cost of a FLACS service.

Using the averaged and nominal values for our theoretical 'hub and spoke' model for FLACS, the use of the FL reduced the weekly theatre requirements from 8 CPS theatre sessions to 2.7 FLACS sessions with both theatres in the FL model running in parallel (total theatre sessions 5.4). This reduced the anticipated running costs of theatres, the ophthalmic day-case unit and staffing costs. However, the laser introduced additional costs into the model (FL equipment, supplies, maintenance and additional staff). Based on the nominal values, even with our hub and spoke model running optimally, the CPS service (average of £433/case) was found to be 86.3% of the cost of the FLACS service (average of £502/case).

The capital cost of the FL when amortised over its lifetime of 10 years was £505/week. Maintenance of the laser was £545/week. The cost of 1 week's worth of PI (n=55) at £135 each was £7356 (figure 2).

The model was not affected when we changed the salary of the laser operator from a midpoint registrar to a band 6 nurse as the hourly rates were of negligible difference (table 1).

Univariate sensitivity analyses were conducted by varying one variable at a time. Minimum and maximum values were obtained from the original data (table 2).

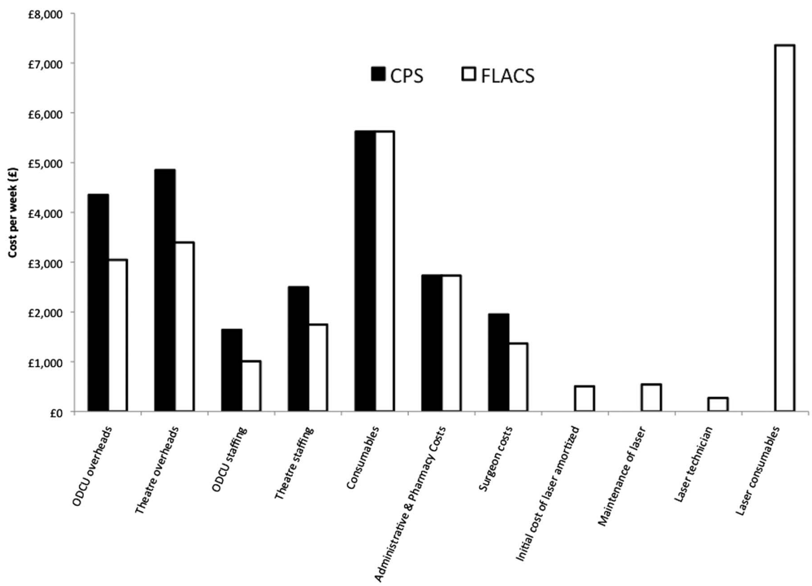

Figure 2 Comparison of the costs per week of conventional phacoemulsification surgery compared with femtosecond laser-assisted cataract surgery.

Table 2 (A) Univariate sensitivity analysis of the hub and spoke model based on range of values from data collected and (B) best-case scenarios for conventional phacoemulsification surgery and femtosecond laser-assisted cataract surgery

Input	Range of values	Values inputted into hub and spoke model	Cost of CPS service compared with FLACS (%)
A			
Cataract workload/week	Minimum	27	82.7
	Average	55	86.3
	Maximum	96	87.8
Number of cataracts on CPS list*	Minimum	5	**108.5**
	Nominal	7	86.3
	Maximum	9	73.8
Number of cataracts on FL list†	Minimum	8	78.6
	Nominal	10	86.3
	Maximum	16	**100.8**
Initial cost of FL	Minimum	£175 000	86.7
	Average	£262 500	86.3
	Maximum	£350 000	85.7
Cost of PI	Minimum	£99	92.8
	Average	£135	86.3
	Maximum	£170	80.5

	Cataract workload/week	Number of cataracts on CPS list	Number of cataracts on FL list	Cost of PI	Cost of CPS/case	Cost of FLACS/case	Cost of CPS service compared with FLACS (%)
B							
Best-case scenario for CPS	27	9	9	135	£371	£515	72.1
Best-case scenario for FLACS	96	5	10	50	£545	£381	143.2

Bold indicates where FLACS is less expensive than CPS option.
*Assuming 10 cases on FLACS list.
†Assuming seven cases on CPS list.

Only when the number of operations on a CPS list was reduced or the number of operations on a FLACS list was increased, could the model give an output in favour of FLACS. Best and worst-case scenarios were constructed for CPS and FLACS, by aligning the most important variables all in favour of one or other modality, with costs of £371 and £515 for CPS and £381 and £545 for FLACS, respectively (table 2B).

Univariate threshold analyses were performed to demonstrate the 'break-even' values of each input. Keeping all other inputs at their original values, the model could not find solutions by which the FL broke even when the capital cost of the FL or the number of operations performed per week was chosen. The costs of the services were equivalent if the true number of cases on a CPS list was 6, or if the FL could increase productivity to 16 cases/each theatre, or if the cost of the laser consumables was reduced to £66. It was thereby ascertained that these three parameters are the most important in this model for determining a cost-neutral scenario for FLACS.

Bivariate sensitivity analyses were performed using combinations of the above inputs. For example, table 3 shows the outcomes of the model when the capacity for the number of cases on CPS and FLACS is simultaneously tested. It shows that the FLACS service would be required to approximately double the number of operations possible during a theatre list for FLACS to break even. Table 4 tests the outcome of the model based on an assumption that the NHS can negotiate lower PI costs based on the provision of a large number of operations per year. It shows that FLACS cannot break even unless the cost of the PI is significantly reduced (to approximately £50 per case). Table 5 compares the cost of the PI against the number of cases on a FLACS list.

DISCUSSION

We have designed a hypothetical treatment delivery model based on a 'hub and spoke' service and utilising FLACS to improve the efficiency of cataract surgery in terms of number of cases undertaken per operating list. We then tested our model with sensitivity and threshold analyses to allow for variations or uncertainties.

Even with our optimised delivery model, FLACS is still more expensive than CPS based on current estimates of costs. To break even, the incorporation of FLACS would

Table 3 Cost of femtosecond laser-assisted cataract surgery versus conventional phacoemulsification surgery

	Number of operations on CPS list (%)				
Number of operations on FLACS list	5	6	7	8	9
8	99.0	87.1	78.6	72.3	67.3
10	**108.5**	95.5	86.2	79.2	73.8
12	**115.9**	**102.0**	92.1	84.7	78.9
14	**121.9**	**107.3**	96.9	89.0	82.9
16	**126.8**	**111.6**	**100.8**	92.6	86.3

Bold indicates where FLACS is less expensive than CPS option.
Bivariate sensitivity analysis: demonstrating relative costs of CPS service compared with FLACS when total number of cases on each theatre list are tested.

Table 4 Cost of femtosecond laser-assisted cataract surgery versus conventional phacoemulsification surgery

	Number of cataract operations per year (%)				
Cost of PI (£)	2000	3000	4000	5000	6000
50	**101.5**	**104.0**	**105.2**	**106.0**	**106.5**
75	95.9	98.1	99.2	99.9	**100.4**
100	90.9	92.8	93.8	94.4%	94.9
125	86.4	88.1	89.0	89.6	89.9
150	82.3	83.8	84.7	85.2	85.5

Bold indicates where FLACS is less expensive than CPS option.
Bivariate sensitivity analysis: demonstrating relative costs of CPS service compared with FLACS when cost of PI and total number of cases per year are tested.

Table 5 Cost of femtosecond laser-assisted cataract surgery versus conventional phacoemulsification surgery

	Number of operations on FLACS list (%)					
Cost of PI	8	9	10	12	14	16
50	92.9	98.6	**103.7**	**112.4**	**119.5**	**125.5**
65	90.0	95.4	**100.1**	**108.2**	**114.8**	**120.3**
80	87.3	92.3	96.7	**104.3**	**110.4**	**115.5**
100	83.9	88.5	92.6	99.5	**105.0**	**109.6**
120	80.8	85.1	88.8	95.1	**100.2**	**104.3**
135	78.6	82.6	86.2	92.1	96.8	**100.7**

Bold indicates where FLACS is less expensive than CPS option.
Bivariate sensitivity analysis: demonstrating relative costs of CPS service compared with FLACS when cost of PI and number of operations on FLACS list are tested.

have to approximately double the number of cataract operations performed per theatre list and indeed could not offer a cost-neutral solution if the number of cases on a CPS theatre list was 8 or more. Our model indicates that the greatest cost impediment to a FLACS service is the price of the PI (average cost £135/case) (figure 2), which represents almost 27% of the total cost per case. Unlike other service costs, the cost of the PI is not mitigated by potential increased productivity. It is therefore a major financial impediment to FLACS ever becoming cost-effective within the NHS, where the total tariff for each operation is fixed between £718 and £932.[16 17] Potentially, this problem may be overcome by the manufacturer considerably discounting this cost to the NHS. In contrast to the PI, our financial model indicates that the costs of the laser itself, staffing and maintenance it were much less important (4.8% of total costs).

There are three important unknowns with regard to our model. First, we are awaiting clinical results from large RCTs comparing FLACS with CPS.[11 12] The latest meta-analysis shows no significant advantages in terms of safety of FLACS over CPS.[10] However, there are advantages in terms of endothelial cell loss, effective phacoemulsification time and unaided visual acuity, albeit no difference in long-term best-corrected visual acuity and an increased risk of anterior capsular tear.[18] We assumed in our financial modelling that there are no differences in outcomes and complication rates between the two procedures. If, however, FLACS were to show significant advantages in terms of patient safety and outcomes then such improvements then this may have additional positive financial implications.

Second, potential gains in productivity from the FL are as yet unpublished and unrealised. Several studies investigating FLACS actually report decreased patient turnover with FLACS.[13 19 20] This is because at present typically the operating surgeon is performing the FL treatment as well as the subsequent lens extraction.

There are as yet no publications on the most effective way to design a FL-centric cataract service. We chose a 'hub and spoke' model based on one FL in a clean room, operated by an ophthalmic surgeon in training or ophthalmic technician/nurse. The FL then fed patients into two independent operating theatres, each with its own surgeon and support staff. This model is theoretical. It needs to be tested in the NHS setting to see if it is viable, and further work may need to be performed to determine a 'best-practice' and optimised efficiency model for FLACS.

Third, it is likely that the costs of the PIs would be reduced below the values quoted to us by the manufacturers, as a large public sector ophthalmology department performing several thousand operations per year could negotiate on costs and capitalise on market competition. As discussed above, this would considerably improve the financial burdens associated with implementing FLACS.

Abell and Vote[13] have previously designed a hypothetical model to derive cost-effectiveness of FLACS. In the absence of better evidence, conservative estimates were used for complication rates with FLACS. Their use of the FL resulted in reducing their theatre efficiency by two cases per list, and subsequently, they estimated the additional cost of FL to be AUS$1065 per case, AUS$750 of which were the direct costs from the FL and AUS$315 from lost productivity. Our model was based on using the laser to improve, rather than impede, productivity. We estimated the cost per case to be £158, of which £135 is the PI. We chose to amortise the costs of the laser over 10 years rather than only 3, but reducing the lifetime of the laser to 3 years increased the cost of each operation to only £180. This demonstrates yet again the greatest cost of FLACS is the cost of the PI rather than the laser itself.

In addition to the above, there are important limitations to mention regarding this hypothetical model. The model assumes that all patients are suitable for a high-volume FLACS theatre list. However, some patients may not be suited to FLACS or to a high-volume service, although the number of contraindications for FLACS is decreasing as experience with the technology improves.[21–23]

Departmental costs used in this model were obtained from a retrospective review of the financial records at four NHS foundation trusts. In order to ensure that the results were applicable to more than just one hospital with its associated population, we selected two teaching hospitals and two district general hospitals of varying sizes, with annual numbers of between ~1400 and 5000 cataract operations. These hospitals serve urban and rural populations (range ~275 000–823 000 served by each hospital) with a mixture of demographics (and include hospitals with one of the highest and one of the lowest cataract tariffs).[17]

The costs of consumables were assumed to be equal for FLACS and CPS. In reality, as the FL performs many stages of the procedure, the cost of some consumables may be reduced (vision blue, cystotome, etc) and some cataracts may no longer require any phacoemulsification.[24] Our model incorporates the salary of a registrar to operate the laser,[25 26] yet if FLACS becomes widely adopted within the UK, then technicians may be trained to perform this duty, perhaps at a reduced cost, but no money was saved when we modelled for the salary of a band 6 nurse to operate the laser.

Overall, this model demonstrates that FLACS could only be financially viable if its implementation into the NHS allowed significant improvements in efficiency in the number of cases treated per theatre list and/or if the cost of the PI was considerably reduced. Further research is required on the clinical outcomes of FLACS compared with CPS as well as real-world evidence of the effect to surgical efficiency afforded by this technology.

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Financial modelling of femtosecond laser-assisted cataract surgery within the National Health Service using a 'hub and spoke' model for the delivery of high-volume cataract surgery

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ARTICLE

A randomized controlled trial comparing femtosecond laser–assisted cataract surgery versus conventional phacoemulsification surgery

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Purpose: To compare the clinical results of conventional phacoemulsification surgery (CPS) with femtosecond laser–assisted cataract surgery.

Setting: Guy's & St Thomas' NHS Foundation Trust, London, United Kingdom.

Design: Single-center prospective randomized interventional case-controlled trial.

Methods: Patients undergoing cataract surgery were randomized to receive either CPS or femtosecond laser–assisted cataract surgery. The surgery was performed with a femtosecond laser (Lensx), and all operations were performed with a gravity-fluidics torsional phacoemulsification machine (Infiniti). The visual acuity, refraction, central corneal thickness (CCT), central foveal thickness (CFT), endothelial cell loss, and rates of intraoperative and postoperative events were recorded. Quality of life outcomes were measured with the EuroQOL 5 dimensions questionnaire (EQ-5D) and patient-reported quality of vision was assessed with a cataract surgery patient-reported outcome measures questionnaire (Cat-PROM5).

Results: The study comprised 400 eyes of 400 patients who had CPS (n = 200) or femtosecond laser–assisted cataract surgery (n = 200). Seven patients (3.5%) in the femtosecond laser–assisted group were not able to complete the treatment and received CPS. The mean uncorrected distance visual acuity (logarithm of the minimum angle of resolution [logMAR]) 0.15 $\pm$ 0.21 (SD) and 0.15 $\pm$ 0.19 logMAR after CPS and femtosecond laser–assisted surgery, respectively (P = 1.0); the pinhole-corrected visual acuity was 0.04 $\pm$ 0.12 and 0.04 $\pm$ 0.12, respectively (P = 1.0); the increase in CCT was 13 $\pm$ 19 μm and 15 $\pm$ 25 μm, respectively (P = .5); and the endothelial cell loss was 9.7 $\pm$ 13.7 % and 10.2% $\pm$ 13.7, respectively (P = .76). The manifest refraction spherical equivalent error was −0.14 $\pm$ 0.60 diopters (D) after CPS and −0.12 $\pm$ 0.60 D after femtosecond laser–assisted surgery (P = .74); the mean change in CFT was 9 $\pm$ 35 μm and 6 $\pm$ 35 μm, respectively (P = .55); and the rate of posterior capsule rupture was 3% and 0%, respectively (P = .03).

Conclusions: This study confirms the nonsignificant differences between 2 treatment modalities, notwithstanding a significant reduction in posterior capsule ruptures in the femtosecond laser–assisted surgery group.

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The introduction of femtosecond laser technology to allow the automation of a number of surgical steps within cataract extraction has been claimed to offer potential advantages of reduced complications and better visual outcomes through greater surgical precision and reproducibility.[1,2] However, systems to undertake femtosecond laser–assisted cataract surgery are expensive to purchase and to use. In a previous study, we estimated

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that femtosecond laser–assisted cataract surgery adds £167 (approximately $220) to each operation within the context of a state-funded healthcare system.[3] From a public health perspective, costs might be mitigated by improved safety leading to increased reliability, a reduced postoperative need for additional clinical or surgical interventions, and better patient outcomes.[4]

Nine randomized controlled trials (RCTs)[1,2,5–11] were identified in a metaanalysis of femtosecond laser–assisted cataract surgery versus conventional phacoemulsification surgery (CPS) by Chen et al.[12,13] There was a statistical reduction in effective phacoemulsification time (EPT) in femtosecond laser–assisted cataract surgery compared with CPS; however, this did not translate into a difference in central corneal thickness (CCT) or endothelial cell count (ECC) at 1 week or beyond. The rates of surgical complications were similar. The postoperative corrected distance visual acuity (CDVA) was statistically superior in the femtosecond laser–assisted surgery group at 1 week and 6 months postoperatively but not at the 1-month to 3-month follow-ups. There was no statistically significant difference in uncorrected distance visual acuity (UDVA) at any timepoint.

Fortunately, the rates of cataract surgery-related events are low. Therefore, large studies are required to be adequately powered to investigate differences in safety. To our knowledge, the largest RCT to investigate complication rates with femtosecond laser–assisted cataract surgery compared with CPS published to date, included 200 eyes and reported 1 anterior capsule tear in the femtosecond laser–assisted surgery group and no events of posterior capsule rupture in either group.[14] With such low rates of complications, such studies are often underpowered to detect differences in safety. To our knowledge, the largest case control study included more than 7000 cataract operations (3371 femtosecond laser–assisted and 3784 CPS) and found an increased risk for vitreous loss in the CPS group (1.4% vs 0.8%).[15]

A recent Cochrane Review of 16 RCTs including 1638 eyes concluded, "There is currently not enough evidence to determine the benefits and harms of laser-assisted cataract surgery compared with standard ultrasound cataract surgery. The evidence is uncertain because current studies have not been large enough to provide a reliable answer to this question."[16]

Our aim was to complete the largest RCT published to date comparing femtosecond laser–assisted cataract surgery with CPS with the intention to inform clinical practice and health policy worldwide. Because there have been a lack of patient-reported outcome measures (PROMs) in previous RCTs, this study aimed to correct this by measuring quality of life with the EQ-5D, a EuroQOL 5 dimensions questionnaire, and patient-reported quality of vision with the Cat-PROM5, a cataract surgery PROMs questionnaire.[17,18]

PATIENTS AND METHODS

The study design was a prospective randomized interventional case-controlled study at a single University Hospital (Guy's & St Thomas' Hospital NHS Foundation Trust, London, United Kingdom) to compare femtosecond laser–assisted cataract surgery with CPS (Clinicaltrials.gov registration number NCT02825693). The study was approved by local Research & Development and Cambridge South Research Ethics Committee (reference 16/EE/0180). The study adhered to the tenets of the Declaration of Helsinki.

The patients were recruited to the study between August 2016 and June 2017. They were screened and recruited, and informed consent was obtained, from routine cataract clinics by members of the trial team (H.W.R., V.K.W.) as per the trial protocol (Version 2.0, 18/05/2016). Table 1 shows the inclusion and exclusion criteria. Within the enrolment visit, patients had a complete ophthalmologic examination. Only one eye per patient was enrolled in the study. Patients were randomized to receive CPS or femtosecond laser–assisted cataract surgery in equal proportions using computer-generated random number tables (Excel software, Microsoft Corp.) just prior to being offered a date for surgery. Excel macros were used to perform the randomization (this was concealed from the allocator) and then the allocation was locked with the patient's research information to address allocation bias. All patients' treatments in this study were delivered by the National Health Service and were free at the point of care. At the follow-up visit, if the patient failed to attend, the patient was contacted and offered another appointment within 1 week. If they failed to attend this, they were considered lost to follow-up from the study.

Data Collection

The outcomes reported in this study are detailed in the trial protocol (version 2.0, 18/05/2016). Data collection for this study occurred at the preoperative assessment, the day of surgery, and the postoperative visit scheduled at 4 weeks after surgery (Table 2). Visual acuity and any investigations performed (corneal topography, specular microscopy, etc.) were conducted by an optometrist or technician (D.S., P.H., D.D.) masked to the participant's treatment arm. Because of the nature of the intervention, neither the surgeon, surgical team, nor the participant could be masked to their treatment arm. All clinical technicians and nurses were masked to the intervention received.

Visual acuities (UDVA, CDVA, and pinhole) were measured with a Snellen chart at 6 m. Participants' refractive errors were collected using an autorefractor (RK-510A, Nidek Co. Ltd.). Biometry was performed using partial coherence interferometry (IOL Master 500, Carl Zeiss Meditec AG). Corneal topography and CCT were determined using a Scheimpflug device (Pentacam, Oculus Optikgeräte GmbH). Macular spectral-domain optical coherence tomography was performed with a modular ophthalmic imaging platform (Spectralis, Heidelberg Engineering GmbH). The ECC was measured with a specular microscope (SP-3000, Topcon Medical Systems, Inc.). Visual comorbidities and risk factors for complications of cataract surgery were recorded prospectively. The risks for posterior capsule rupture were calculated for patients using a composite risk calculation system.[20]

The PROMs were collected with the Cat-PROM5 tool, a recently developed National Institute for Health Research–funded questionnaire consisting of 5 questions that provide a Rasch calibrated psychometrically robust measure, which is highly responsive to cataract surgery, in which a higher score indicates greater visual disability.[17,18]

The quality of life outcomes were assessed using the EuroQOL EQ-5D questionnaire, which consists of 2 components: 5 questions about 5 dimensions of health-related quality of life (mobility, self-care, usual activities, pain/discomfort, and anxiety/depression), which are scored as 1, 2, or 3 (1 meaning no problems and 3 meaning extreme problems). The 5 responses are then weighted and combined to create a summary index with values 0 to 1, where 1 indicates no problems. The visual analogue scale is a continuous scale anchored by best imaginable and worst imaginable health, with values ranging from 0 to 100 (where 100 indicates best possible health). The EQ-5D was chosen because it is well recognized by public bodies (such as the National Institute for Health and Care Excellence) for comparative health economic analyses.[19]

Table 1. Inclusion and exclusion criteria for enrolment in the study.

Inclusion Criteria:
- Patients must have reduced visual acuity or visual symptoms attributed to the presence of cataract in 1 or both eyes by the examining ophthalmologist or must require cataract surgery on clinical grounds other than visual symptoms.
- Patients must be willing to attend follow-ups 3 to 4 weeks after cataract surgery.
- Patients must have sufficient English language for informed consent and completion of the patient-reported outcome questionnaires.

Exclusion Criteria:
- Children below the age of 18
- Already enrolled in another study
- Clinical contraindications for femtosecond laser–assisted cataract surgery, such as:
  - Significant corneal opacities
  - Small pupils (<4.0 mm) after pharmacological dilatation
  - Patients unable to lie sufficiently flat so as to be positioned underneath the laser machine.

Table 2. Schedule for data collection.

Parameter	Baseline	Day of Surgery	Postop Visit (3–4 Wk)
Baseline demographics	X		
UDVA	X		X
CDVA	X		
PHVA	X		X
IOP	X		X
Risk factors for cataract surgery[19]	X		
Inclusion/exclusion criteria	X	X	
Refractive error	X		X
Keratometry	X		
Biometry	X		
Corneal topography	X		X
ECC	X		X
OCT of the macula	X		X
EQ-5D-3L	X		X
Cat-PROM5	X		X
Adverse event collection		X	X

Cat-PROM5 = cataract surgery patient-reported outcome measures questionnaire; CDVA = corrected distance visual acuity; ECC = endothelial cell count; EQ-5D-3L = EuroQOL 5 dimensions questionnaire, 3 level version; IOP = intraocular pressure; OCT = optical coherence tomography; PHVA = pinhole visual acuity; UDVA = uncorrected distance visual acuity

The femtosecond laser–assisted cataract surgery was performed using a femtosecond laser (Lensx, Alcon Laboratories, Inc.). Two surgeons (H.W.R., V.K.W.) received training and full accreditation on the device in anticipation of this trial and performed at least 30 laser applications each before the trial began. The femtosecond laser was used to perform capsulotomy, lens fragmentation ± astigmatic keratotomies. Default laser parameters for all surgeons are detailed in Supplement 1 (available at http://jcrsjournal.org). When the laser treatment could not be performed for some reason (eg, repeated inability to dock, laser machine fault, etc.) patients underwent surgery in accordance with conventional CPS. Astigmatic keratotomies within the femtosecond laser–assisted group or limbal relaxing incisions (LRIs) within the CPS group were offered to any patient with corneal astigmatism greater than 0.9 diopters (D) based on corneal topography. The astigmatic results are presented elsewhere.[21] All cataract operations were performed under a local anesthetic. All operations were unilateral, and no other additional procedures were planned, other than arcuate keratotomies for the reduction of corneal astigmatism.

After the femtosecond laser treatment, the patient was transferred to the operating theater for the remainder of the cataract extraction. Phacoemulsification was performed using the gravity-fluidics torsional phacoemulsification machine (Infiniti, Alcon Laboratories, Inc.) Patients undergoing CPS were prepared for surgery in the same way as those in the laser arm. Rather than receiving laser pretreatment, they were brought straight to the operating theater. The default intraocular lens (IOL) used for in-the-bag placement was a hydrophobic acrylic IOL (Acrysof SA60AT, Alcon Laboratories, Inc.). All operations were performed by surgeons who had completed at least 30 femtosecond laser–assisted cataract surgery procedures (H.W.R., V.K.W., D.O.B.).

Statistical Analysis

Table 3 shows the baseline characteristics for each treatment arm. The results were analyzed primarily as per intention to treat. The evaluators were masked to the participants' treatment arm. For all evaluations of visual acuity as an outcome, patients with visually significant ocular comorbidities were excluded prospectively. Snellen visual acuities were converted to logarithm of the minimum angle of resolution (logMAR) for analysis.[22] Continuous data were reported using means ± SDs if the data appeared Gaussian. Binary data were reported as frequencies and percentages and evaluated with the Fisher exact test. Student *t* tests were used for parametric data. All statistical tests used a 2-sided *P* value of $\alpha = 0.05$, unless otherwise specified. Intraoperative or postoperative adverse events were defined as any event that involved unintentional trauma to an ocular structure, requiring additional treatment or having a negative effect on participants' eyesight. The EQ-5D index scores were calculated using the visual analogue score method calibrated for the U.K. The Rasch-calibrated Cat-PROM5 scores (logits) were calculated from the questionnaire responses in accordance with the developer's instructions.[16]

The UDVA at 4 weeks was designated as the primary outcome with intraoperative and postoperative complications, refraction, corneal thickness, and endothelial cell loss, with quality of life outcomes and patient-reported quality of vision preoperatively and at 4 weeks postoperatively selected as secondary outcomes. A priori calculations for sample size indicated a total sample size of 370 to have an 85% chance of detecting a 0.1 difference in logMAR visual acuity and assumption of $\sigma = 0.32$ with $\alpha = 0.05$ and a 2-tailed analysis. This sample size was rounded to 400 to account for the possibility of patients lost to follow-up.

RESULTS

Of the 427 patients who were recruited to the study, 27 patients withdrew from the trial before surgery. Therefore, 400 eyes of 400 patients received surgery between November 2016 and June 2017 (200 CPS, 200 femtosecond laser-assisted). Nine patients (2.3%) failed to attend their follow-up appointments. Seven (3.5%) of the 200 patients in the CPS group compared with 2 (1.0%) of the 200 patients in the femtosecond laser–assisted group were lost to follow-up ($P = .17$). Only one of the participants lost to follow-up had an untoward clinical event (CPS arm), requiring referral to vitreoretinal colleagues, and withdrew from providing further information to the study team; the remainder had uneventful clinical courses (further clinical information on those lost to follow-up is in Supplement 2,

Table 3. Baseline characteristics in the 2 treatment arms.

Parameter	Femtosecond Laser–Assisted Cataract Surgery	CPS
Sex, Male/female (n)	100/100	82/118
1st eye/2nd eye (n)	162/38	168/32
Right eye/left eye (n)	107/93	109/91
Mean age (y)	69.9 ± 10.9	70.5 ± 9.8
Mean preop CDVA (logMAR)	0.62 ± 0.49	0.54 ± 0.46
Mean SE refractive error (D)	−0.17 ± 2.99	−0.77 ± 4.88
Mean AL (mm)	23.88 ± 1.55	23.63 ± 1.26
Mean ACD (mm)	3.25 ± 0.42	3.21 ± 0.44
Mean target refraction (D)	−0.21 ± 0.34	−0.22 ± 0.4
Mean IOP (mm Hg)	13.7 ± 4.1	13.9 ± 3.6
Mean CCT (μm)	541 ± 49	546 ± 35
Mean ECD (cells/mm^2)	2505 ± 313	2534 ± 327
Mean CFT (μm)	199 ± 47	189 ± 33
Mean predicted PCR risk (%)[20]	1.63 ± 0.91	1.59 ± 1.29
Mean CAT-PROM5 calibrated score	0.45 ± 2.6	0.28 ± 2.31
Mean EQ-5D-3L index score	0.82 ± 0.19	0.80 ± 0.23
Mean EQ-5D visual analogue scale	77.84 ± 16.53	75.17 ± 18.63
Complicated cataracts		
Posterior polar cataracts (n)	2	1
Mature brunescent cataracts (n)	2	3
White cataracts (n)	7	6
Subluxated cataracts (n)	0	0

Means ± SD
ACD = anterior chamber depth; AL = axial length; Cat-PROM5 = cataract surgery patient-reported outcome measures questionnaire; CCT = central corneal thickness; CDVA = corrected distance visual acuity; CFT = central foveal thickness; CPS = conventional phacoemulsification surgery; ECD = Endothelial cell density; EQ-5D = EuroQOL 5 dimensions questionnaire; EQ-5D-3L = EuroQOL 5 dimensions questionnaire, 3 level version; IOP = intraocular pressure; logMAR = logarithm of the minimum angle of resolution; PCR = posterior capsule rupture; SE = spherical equivalent

available at http://jcrsjournal.org). Although losses to follow-up were unequal between the arms, the high overall rate of follow-up of 97.8% suggests that possible biases resulting from unequal follow-ups are unlikely to be important.

One hundred eighty-two (45.5%) of the 400 study patients were men, and 330 (82.5%) of the operations were performed in first eyes, 216 (54%) of the 400 eyes were right-eye operations. The mean age of the patients was 70.2 ± 10.4 years. The mean preoperative CDVA was 0.58 ± 0.47 logMAR. Table 3 shows the patient demographics and full baseline data. Clinical and self-reported questionnaire measures were similar between the 2 groups. Of the 400 operations, 155 (39.0%) were performed with the main incision within ±30 degrees of the steep axis, 314 (78.5%) were performed with the main incision sited at the corneal limbus, and 86 (21.5%) with clear corneal incisions. Forty-nine (12.3%) of the 400 patients were excluded from postoperative visual acuity analysis because of preexisting visually significant ocular comorbidities (28 in the femtosecond laser–assisted group, 21 in the CPS group).

Table 4. Case distribution between the 3 surgeons and between the 2 treatment arms (P = .99).*

Parameter	Surgeon 1	Surgeon 2	Surgeon 3	Total
Conventional phacoemulsification surgery	68	87	45	200
Femtosecond laser–assisted cataract surgery	69	86	45	200
Total	137	173	90	400

*Chi-square test

The cases were distributed evenly between the 3 surgeons and between the 2 treatment arms (P = .99) (Table 4).

The femtosecond laser treatment was delivered successfully to 96.5% of cases. Patients receiving femtosecond laser–assisted cataract surgery treatment spent a mean time of 5.9 ± 2.0 minutes in the laser room. Seven patients (3.5%) were unable to receive femtosecond treatment and received CPS. The reasons were as follows: repeated bubbles in interface/flat cornea (n = 1), administrative error (n = 1), patient compliance (n = 2), and patient's palpebral aperture too narrow (n = 3). One of these patients suffered an intraoperative suprachoroidal hemorrhage; the others experienced uneventful operations. The mean number of docking attempts was 1.3 ± 0.7 per patient. Supplement 1 (available at http://jcrsjournal.org) shows the reasons for failed attempts at docking and details of the laser treatments delivered. The mean duration of surgical time was 11.7 ± 3.5 minutes for femtosecond laser–assisted treatment and 14.7 ± 6.8 minutes for CPS.

The mean UDVA (logMAR) after CPS was 0.15 ± 0.21 and 0.15 ± 0.19 after femtosecond laser–assisted cataract surgery treatment (P = 1.0), and the mean pinhole-corrected visual acuity was 0.04 ± 0.12 and 0.04 ± 0.12, respectively (P = 1.0) (Figures 1 to 4). The mean increase in CCT was 13 ± 19 μm after CPS and 15 ± 25 μm after femtosecond laser–assisted surgery (P = .5). The ECC loss was −9.7 ± 13.7% after CPS and −10.2 ± 13.7% after femtosecond laser–assisted surgery (P = .76). The refractive mean spherical equivalent error was −0.14 ± 0.60 D after CPS and −0.12 ± 0.60 D after femtosecond laser–assisted surgery (P = .74) (Figures 5 to 8). The mean change in the central foveal thickness was 9 ± 35 μm after CPS and 6 ± 35 μm after femtosecond laser–assisted surgery (P = .55) (Table 5). The Cat-PROM5 demonstrated a substantial shift between preoperative to postoperative completions, signaling a significant self-reported reduction in visual difficulty after surgery that was similar in the 2 intervention groups. The EQ-5D summary index similarly reflected an improved score that was similar in the 2 groups. The EQ-5D visual analogue score, however, was unchanged in the femtosecond laser–assisted surgery group but increased in the CPS group (Table 5). There were no differences in total rates of intraoperative or postoperative complications (Tables 6 and 7). There was a significant

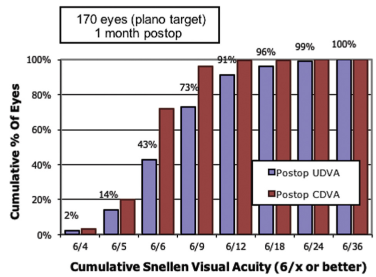

Figure 1. Uncorrected distance visual acuity and CDVA at 1 month after femtosecond laser–assisted cataract surgery (CDVA = corrected distance visual acuity, UDVA = uncorrected distance visual acuity).

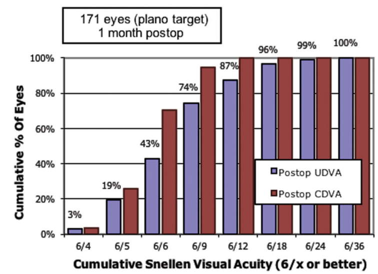

Figure 2. Uncorrected distance visual acuity and CDVA at 1 month after conventional phacoemulsification surgery (CDVA = corrected distance visual acuity, UDVA = uncorrected distance visual acuity).

difference in the rate of posterior capsule rupture with a higher rate occurring in the CPS group ($P = .03$).

DISCUSSION

To our knowledge, this is the largest RCT published to date, comparing the safety and effectiveness of femtosecond laser–assisted cataract surgery versus CPS and including 400 eyes of 400 patients. All surgeries were performed at a single center by 3 surgeons who had previously completed their femtosecond laser–assisted surgery learning curve, having completed at least 30 cases. Patients were reviewed at 4 weeks postoperatively to perform clinical examination, assess for complications, and gather postoperative data.

Overall, these results point overwhelmingly to an absence of clinical differences between femtosecond laser–assisted cataract surgery treatment and CPS (except for posterior capsule rupture and the EQ-5D visual analogue scale). In many aspects, our findings are congruous with the available evidence and on occasion are in contrast with conventional understanding.

Previously reported gains in visual acuity after femtosecond laser–assisted surgery tended to be early (1 week postoperatively) or late (at 6 months) but not between the 1- to 3-month timepoints.[13,23] In the current study, we chose to evaluate patients at 4 weeks when the majority of postoperative edema and inflammation has settled. At this timepoint, we found no difference in the postoperative visual acuity between the 2 groups (Figures 1 and 2, Table 5). We did not perform an immediate postoperative evaluation, although in accordance with our hospital protocol, all patients were contacted by telephone to report and document any problems. It might be the case that femtosecond laser–assisted cataract surgery is better in the early postoperative phase because of reduced ultrasound energy and reduced corneal edema resulting in faster visual rehabilitation, followed by equivalence in the interim, with any late differences perhaps

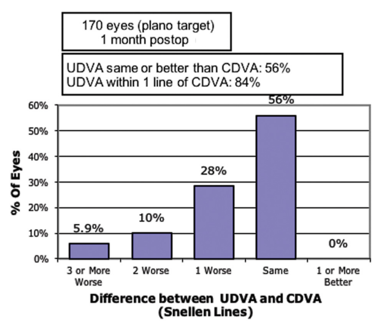

Figure 3. Difference between UDVA and CDVA at 1 month after femtosecond laser–assisted cataract surgery (CDVA = corrected distance visual acuity, UDVA = uncorrected distance visual acuity).

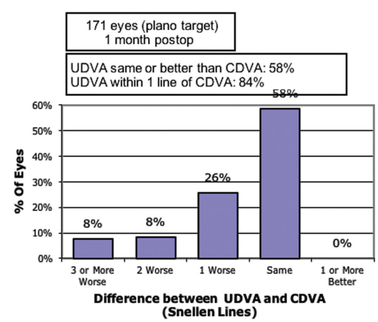

Figure 4. Difference between UDVA and CDVA at 1 month after conventional phacoemulsification surgery (CDVA = corrected distance visual acuity, UDVA = uncorrected distance visual acuity).

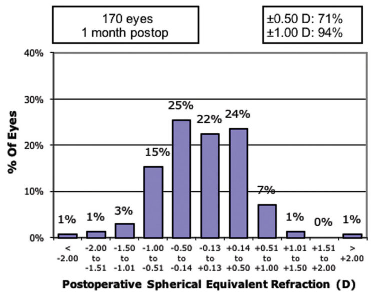

Figure 5. Spherical equivalent refractive accuracy at 1 month after femtosecond laser–assisted cataract surgery.

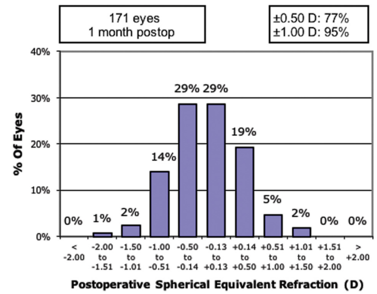

Figure 6. Spherical equivalent refractive accuracy at 1 month after conventional phacoemulsification surgery.

because of differences in late lens decentration or posterior capsule opacification.[24–26] It is of note that we found no differences in CCT or endothelial cell loss at 1 month postoperatively, which might be expected if early corneal edema delaying visual rehabilitation was a significant problem. At present, we are also evaluating these patients at 12 months postoperatively to determine late differences, and these results will be reported later.

No differences were found in the intraocular pressure (IOP) change between the 2 groups. Because the patients were reviewed at 4 weeks, the postoperative IOP rises might have gone unnoticed. In the 2 patients seen with raised IOP postoperatively, both were presumed to be attributable to a steroid response. Furthermore, no patients with extremely high IOPs presented to our service during the early postoperative phase.

To our knowledge, this is the first large-scale randomized controlled trial to evaluate rates of cystoid macular edema (CME) between femtosecond laser–assisted cataract surgery and CPS. Our rates of CME were equivalent between the 2 groups, and there was no overall difference in the mean change in central foveal thickness. This is in keeping with the available evidence.[9,27] Of the 7 cases of CME in this study, the risk factors were prospectively identified for 5 cases (previous macula off retinal detachment = 1, previous epiretinal membrane peel = 1, previous central retinal vein occlusion = 1, epiretinal membrane = 2).

Our study found a statistically significant increase in the rate of posterior capsule rupture in the CPS group. This is an important finding because of the associated risks for further complications during the postoperative phase associated with increased morbidity and costs.[4,28] The Cochrane review of published RCTs[23] found an overall rate of posterior capsule rupture in zero of 529 cumulative femtosecond laser–assisted cataract surgery cases compared with 1 (0.1%) of 547 CPS cases. We consider the rates of posterior capsule rupture in both of those groups to be lower than expected; perhaps reflecting patient selection for the studies, the expertise of the surgeons, or both. The EUREQUO case-control study, which compared

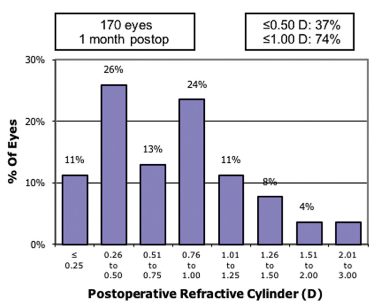

Figure 7. Postoperative refractive cylinder at 1 month after femtosecond laser–assisted cataract surgery.

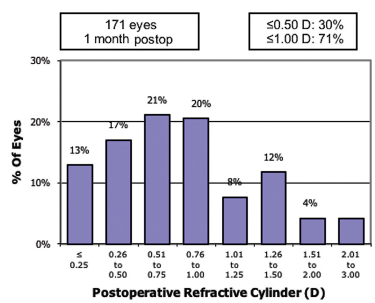

Figure 8. Spherical equivalent refractive accuracy at 1 month after conventional phacoemulsification surgery.

Table 5. Postoperative results in the 2 treatment arms.

Parameter	Femtosecond Laser–Assisted Cataract Surgery	CPS	*P* Value
Mean UDVA (logMAR)	0.15 ± 0.19	0.15 ± 0.21	1.0
Mean PHVA (logMAR))	0.04 ± 0.12	0.04 ± 0.12	1.0
Mean change in IOP (mm Hg)	−1.3 ± 4.5	−1.7 ± 3.8	.45
Mean phacoemulsification energy (CDE)	9.6 ± 7.0	11.1 ± 9.8	.08
Mean change in CCT (μm)	15 ± 25	13 ± 19	.50
Mean ECL (%)	10.2 ± 13.7	9.7 ± 13.7	.76
Mean change in CFT (μm)	6 ± 35	9 ± 35	.55
Mean arithmetic SE refractive error from target refraction (D)	−0.01 ± 0.56	0.04 ± 0.58	.39
Mean absolute SE refractive error from target refraction (D)	0.42 ± 0.40	0.40 ± 0.46	.65
SE refraction within ±0.5 D of intended (%)	67.3	72.3	.32
SE refraction within ±1.0 D of intended (%)	92.9	93.7	.84
Mean change in Cat-PROM5 calibrated score	−2.44 ± 3.13	−2.22 ± 2.89	.49
Mean change in EQ-5D-3L index score	0.03 ± 0.17	0.03 ± 0.16	1.0
Mean change in EQ-5D visual analogue scale	0.71 ± 13.61	4.18 ± 13.91	.02*

Means ± SD
Cat-PROM5 = cataract surgery patient-reported outcome measures questionnaire; CCT = central corneal thickness; CDE = cumulative dissipated energy; CFT = central foveal thickness; CPS = conventional phacoemulsification surgery; ECL = endothelial cell loss; IOP = intraocular pressure; logMAR = logarithm of the minimum angle of resolution; PHVA = pinhole visual acuity; SE = spherical equivalent; UDVA = uncorrected distance visual acuity
*Statistically significant

2814 femtosecond laser–assisted cataract surgery cases with 4987 CPS cases,[29] found no significant difference in the posterior capsule rupture rates of 0.4% and 0.7% (P = .79), respectively. The 2 other largest studies of note included a case series of over 7000 surgeries in the public sector in the United States, which found a greater rate of vitreous loss in the CPS group,[15] and a case-control study of more than 4000 patients, which found no significant difference in posterior capsule rupture rates.[30] Our study was performed in the public sector in a hospital based within an inner-city area of London, U.K., with the accompanying demographics and high rates of comorbidities. Of the patients sustaining posterior capsule rupture in our cohort, the mean composite risk calculation score was 2.04% (range 0.84% to 3.13%),[20] suggesting that although on the high side, the 3% rate in the CPS arm of our study was at least in part a reflection of the surgical case complexity in our patient cohort. As such, femtosecond laser–assisted cataract surgery might carry more of an advantage in cohorts that have an existing higher rate of posterior capsule rupture (ie, in tertiary units performing complex cataract surgery, surgeons in training, or in this case, both) and conversely the benefits of femtosecond laser–assisted surgery might be more limited in simpler case mixes. The benefits of femtosecond laser–assisted cataract surgery for surgeons in training have been described previously.[31]

All but one of the posterior capsule ruptures in the CPS group occurred during the phacoemulsification grooving or segment removal stages. The lower rate of posterior capsule rupture in the femtosecond laser–assisted group could imply that these stages of the operation are facilitated most by the femtosecond laser. The nuclear segmentation patterns of the femtosecond laser might produce more regular nuclear segments after cracking that might assist the

Table 6. Intraoperative events.

	Number of Events (%)		
Parameter	Femtosecond Laser–Assisted Cataract Surgery	CPS	*P* Value
Anterior capsule tear	6 (3)	3 (1.5)	.50
Descemet membrane tear	2 (1)	0	.50
IFIS/iris trauma	3 (1.5)	8 (4)	.22
Residual soft lens matter	1 (0.5)	0	1.0
IOL exchange	1 (0.5)	0	1.0
Suprachoroidal hemorrhage*	1 (0.5)	0	1.0
Posterior capsule tear	0	6 (3)	.03†
Vitreous loss	0	5 (2.5)	.06
Dropped lens fragments	0	3 (1.5)	.25
Zonular dialysis	0	1 (0.5)	1.0
Total	14 (7)	17 (8.5)	.71

CPS = conventional phacoemulsification surgery; IFIS = intraoperative floppy-iris syndrome; IOL = intraocular lens
*This patient was randomized to the femtosecond laser–assisted group but received CPS
†Statistically significant

Table 7. Postoperative events.

Parameter	Number of Events (%)		*P* Value
	Femtosecond Laser–Assisted Cataract Surgery	CPS	
Corneal edema	4 (2)	2 (1)	.69
Return to OT on day 1 for suspected vitreous in AC	0	1 (0.5)	1.0
CME	4 (2)	3 (1.5)	1.0
Prolonged anterior uveitis*	2 (1)	0	.50
Steroid response/postop raised IOP	2 (1)	0	.5
Return to OT for residual soft lens matter in bag	1 (0.5)	0	1.0
Suture abscess	0	1 (0.5)	1.0
Hypotony	0	1 (0.5)	1.0
Suprachoroidal hemorrhage	0	1 (0.5)	1.0
Total	11 (6.5)	5 (2.5)	.20

AC = anterior chamber; CME = cystoid macular edema; CPS = conventional phacoemulsification surgery; IOP = intraocular pressure; OT = operating theater

*Both patients were randomized to the femtosecond laser–assisted group but one received CPS

surgeon by ensuring a more reproducible stage 2. This is certainly our anecdotal experience, and it is also reflected by the shorter surgical time in the femtosecond laser–assisted surgery group.

It is worth noting that the difference in posterior capsule rupture rates was only just statistically significant. One more posterior capsule rupture in the femtosecond laser–assisted group or one less in the CPS group would have rendered this result not statistically significant (and the risk for type 2 error is increased when analyzing outcomes with smaller numbers). However, it was possible to compare observed rates of posterior capsule rupture with expected rates because this study prospectively risk stratified patients according to a composite risk calculation system.[20,28]

Self-reported visual difficulty and quality of life outcomes were interesting. The Cat-PROM5 scores overall shifted significantly toward less visual difficulty with similar reductions in each group. The EQ-5D scores likewise shifted toward better quality of life outcomes postoperatively, with similar improvements in each group. There was a significant increase in the EQ-5D visual analogue score after CPS compared with femtosecond laser–assisted cataract surgery ($P = .02$). However, in the absence of a plausible clinical explanation or safety issue, and because we found no differences in the EQ-5D-3L index score ($P = 1.0$) or Cat-PROM5 calibrated score ($P = .49$), we cannot suggest any reason why this result is not a type 1 statistical error. Furthermore, the EQ-5D visual analogue score is known to correlate poorly with the impact of cataract surgery.[32]

Our anterior capsular tear rate was greater in the femtosecond laser–assisted group (3% versus 1.5%); however, this was not statistically significant. The anterior capsule tear rates in other RCTs were, again, exceptionally low. However, Abell et al.[30] found an increased risk for anterior capsule tears with femtosecond laser–assisted cataract surgery compared with CPS, reflecting the postage-stamp edge microanatomy of the capsulotomy rim.[10,11,26,33] In our anecdotal experience, the femtosecond laser–assisted anterior capsulotomy is indeed more likely to tear than a manual continuous curvilinear capsulorhexis. This resulted in each surgeon adapting their surgical technique during each of our learning curves, that is, not to overly stretch the capsulotomy by removing large and dense fragments. This is in turn facilitated by predictable capsulotomy and lens fragmentation sizes created by the femtosecond laser.

In contrast with other studies, we did not find that femtosecond laser–assisted cataract surgery resulted in more predictable refractive outcomes than CPS.[1,8,26] Our overall median absolute error (0.32 D for femtosecond laser–assisted surgery and 0.29 D for CPS) and proportions within ±0.5 D and ±1.0 D were similar between both groups and in keeping with other studies in the literature (Figures 5 and 6). However, in a subgroup analysis of this same study, we have shown better outcomes with femtosecond laser astigmatic keratotomies compared with manual limbal relaxing incisions.[21]

One more surprising result is that we did not realize the reduction in phacoemulsification energy (cumulative dissipated energy [CDE]) previously reported with femtosecond laser–assisted cataract surgery (9.6 ± 7.0) compared with CPS (11.1 ± 9.8) ($P = .08$). This was a nonsignificant result, although perhaps our preference for segmentation of the cataract rather than fragmentation into cubes might have been a factor. Two studies[34,35] have demonstrated reduced ultrasound energy with femtosecond laser–assisted cataract surgery but with using either a grid pattern or segmentation with multiple concentric cylinders. Shajari et al.[36] recently published their findings that CDE was reduced with the grid pattern compared with the segmentation pattern, which was our preferred technique. It follows, therefore, that the grid pattern softens the nucleus and permits more phacoaspiration, reducing CDE, in comparison with a segmentation pattern, which requires a nuclear disassembly technique resembling a divide-and-conquer procedure.

Previous studies have indicated that incorporating a femtosecond laser can have a negative impact on productivity, which can largely be attributed to transfer time between the laser and the surgical bed.[37–39] Although we did not directly measure this transfer time, we have reported on the hub-and-spoke model we used for the femtosecond laser service and found that this resulted in marginal gains in productivity in the femtosecond laser–assisted group.[40]

The limitations of this study include that many clinical outcomes were evaluated leading to an increased risk for type 1 statistical errors. Furthermore, RCTs are often underpowered for safety, and complications in cataract surgery are fortunately rare (making it harder to meaningfully evaluate). For example, one patient randomized to femtosecond laser–assisted surgery sustained a suprachoroidal hemorrhage. A case of suprachoroidal hemorrhage with femtosecond laser–assisted cataract surgery has been reported in the literature; however, at present, it is not known whether supraphysiological vacuum applied to the globe further increases the risk for this rare but potentially devastating complication.[41] The sample size required to test for such rare complications would be unfeasibly large.

This RCT compares the clinical outcomes of femtosecond laser–assisted cataract surgery and CPS and confirms, in the majority, the nonsignificant differences between the 2 treatment modalities in terms of visual, refractive, and a range of other clinical and patient-reported outcomes, while suggesting a higher rate of posterior capsule tears after conventional phacoemulsification.

WHAT WAS KNOWN

- Metaanalyses of several small RCTs showed little overall differences in visual and refractive outcomes between femtosecond laser–assisted cataract surgery and CPS.
- Little was known about whether a difference existed regarding PROMs after femtosecond laser–assisted cataract surgery or CPS.

WHAT THIS PAPER ADDS

- This was the largest RCT to date to demonstrate nonsignificance in clinical outcomes and PROMs between femtosecond laser–assisted cataract surgery and CPS.
- Femtosecond laser–assisted cataract surgery might reduce the risk for posterior capsular rupture.

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Evaluation of a hub-and-spoke model for the delivery of femtosecond laser-assisted cataract surgery within the context of a large randomised controlled trial

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ABSTRACT

Aims To test a hypothesis that cataract operating room (OR) productivity can be improved with a femtosecond laser (FL) using a hub-and-spoke model and whether any increase in productivity can offset additional costs relating to the FL.

Methods 400 eyes of 400 patients were enrolled in a randomised-controlled trial comparing FL-assisted cataract surgery (FLACS) with conventional phacoemulsification surgery (CPS). 299 of 400 operations were performed on designated high-volume theatre lists (FLACS=134, CPS=165), where a hub-and-spoke FLACS model (1×FL, 2×ORs=2:1) was compared with independent CPS theatre lists. Details of operative timings and OR utilisation were recorded. Differences in productivity between hub-and-spoke FLACS and CPS sessions were compared using an economic model including testing hypothetical 3:1 and 4:1 models.

Results The duration of the operation itself was 12.04±4.89 min for FLACS compared with CPS of 14.54±6.1 min (P<0.001). Total patient time in the OR was reduced from 23.39±6.89 min with CPS to 20.34±5.82 min with FLACS (P<0.001)(reduction of 3.05 min per case). There was no difference in OR turnaround time between the models. Average number of patients treated per theatre list was 9 for FLACS and 8 for CPS. OR utilisation was 92.08% for FLACS and 95.83% for CPS (P<0.001). Using a previously established economic model, the FLACS service cost £144.60 more than CPS per case. This difference would be £131 and £125 for 3:1 and 4:1 models, respectively.

Conclusion The FLACS hub-and-spoke model was significantly faster than CPS, with patients spending less time in the OR. This enabled an improvement in productivity, but insufficient to meaningfully offset the additional costs relating to FLACS.

INTRODUCTION

Over the past decade, femtosecond lasers (FLs) have been introduced into the field of cataract surgery to try to automate the procedure and more importantly improve both efficacy and safety.[1] Multiple prospective case series have been published which appear to support its potential in cataract surgery and more surgeons are adopting this new technology.[1–6] A recent Cochrane review of 16 randomised-controlled trials (RCTS) including 1638 eyes concluded, 'There is currently not enough evidence to determine the benefits and harms of laser-assisted cataract surgery compared with standard ultrasound cataract surgery. The evidence is uncertain because current studies have not been large enough to provide a reliable answer to this question'.[7]

Until good quality evidence is available describing better clinical outcomes, it is not possible to currently support the widespread introduction of FL-assisted cataract surgery (FLACS) within public healthcare organisations such as the National Health Service (NHS). This is especially pertinent as by the very nature of its complex technology, FLACS has significant associated financial costs, including initial purchase costs of the laser itself, servicing, depreciation and the individual patient interfaces (PI). These costs seriously question its financial viability, especially in healthcare systems funded by the state. In addition, current published studies with FLACS report increased total surgical time and therefore reduced patient turnover and productivity.[8–10] This is because the operating surgeon in these studies is typically performing both the FL treatment and the subsequent lens extraction within the operating room (OR). This reduction in productivity is highly important within the public health sector, where high-volume surgical models are necessary to meet the both the increasing numbers of patients requiring cataract surgery and economic limitations. It is of note that the current published literature on the economics of FLACS mainly originates from healthcare systems within the private sector, where supplementary costs of advanced technologies may to a certain extend be passed onto the patient in the form of a copayment system.[8] However, even in such healthcare models, the literature advocates that FLACS at this time is not cost-effective.[8]

Despite these considerations, FLACS does offer the promise to automate a number of the component parts of cataract surgery so that they do not need to be undertaken by an appropriately trained ophthalmic surgeon within the OR. Surgical steps such as corneal incisions, arcuate keratotomies, capsulotomies and nuclear lens division can be undertaken with FL by a doctor in training or suitably accredited and trained nurse/technician in a clean room. This has the potential to reduce the amount of time each individual patient spends in the OR with the ophthalmic surgeon. As a result, the efficiency of cataract surgery might be improved by increasing the number of surgical cases undertaken in a given time period. This potential efficiency is

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Box 1 Inclusion and exclusion criteria for enrolment into the study

Inclusion criteria

- Patients must have reduced visual acuity or visual symptoms attributed to the presence of cataract in one or both eyes by the examining ophthalmologist or else must require cataract surgery on clinical grounds other than visual symptoms.
- Patients must be willing to attend for follow-up at 3–4 weeks after cataract surgery.
- Patients must have sufficient English language for informed consent and completion of the patient reported outcome questionnaires.

Exclusion criteria

- Children below the age of 18 years
- Patients already enrolled in another study
- Clinical contraindications for femtosecond laser-assisted cataract surgery, such as
  - Significant corneal opacities
  - Small pupils (<4 mm) following pharmacological dilatation
  - Patients unable to lie sufficiently flat so as to be positioned underneath the laser machine.

increased if a 'hub-and-spoke' model is used, with a single FL treating and then feeding patients into several ORs for completion of surgery. Potentially, if the number of cases per theatre session can be increased sufficiently, then the additional costs associated with FL technology might be offset. In a previous publication, we have previously explored this possibility using a hypothetical model based on real-world financial data.[11] We reported that in order to break even, there would need to be, for example, a 43% increase in the number of operations performed per theatre list accompanied by a need to discount the cost of the PIs by at least 52% by the manufacturers.[2]

As yet, there are no publications looking at the efficacy, safety and additionally the economics of FLACS compared with conventional phacoemulsification surgery (CPS), within a 'hub-and-spoke' model, as described above, in a real-world public health sector setting, where both trainee and fully accredited surgeons undertake surgery, with all the constraints that can be associated with the Public Health Sector, such as limited financial resources, OR space and resistance to change in formalised working practices. In order to investigate some of these issues, we undertook an RCT comparing FLACS with CPS, in which we delivered our FLACS service using a hub-and-spoke model. Surgeries were performed by three cataract surgeons of differing levels of experience (one fully accredited with 20 years' experience, one newly accredited and one specialist registrar).

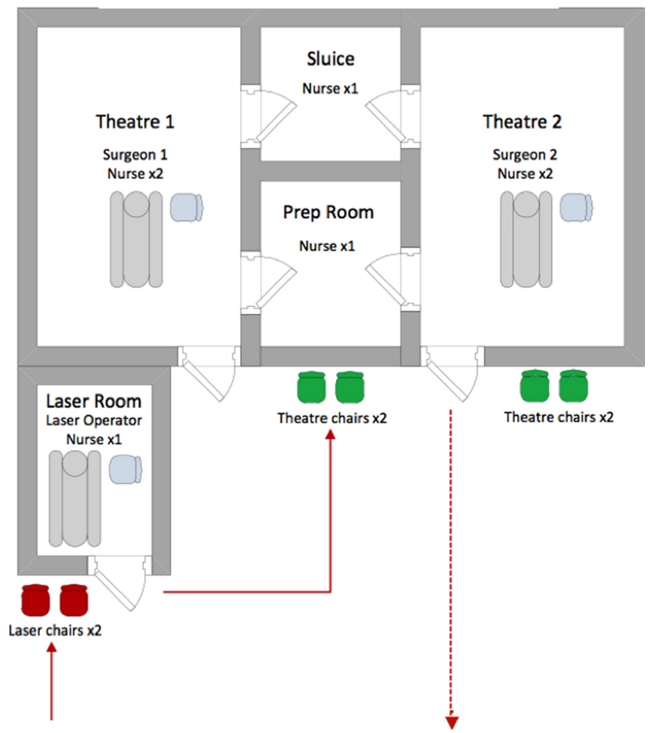

Figure 1 St Thomas' Hospital's 'hub-and-spoke' model for femtosecond laser-assisted cataract surgery.

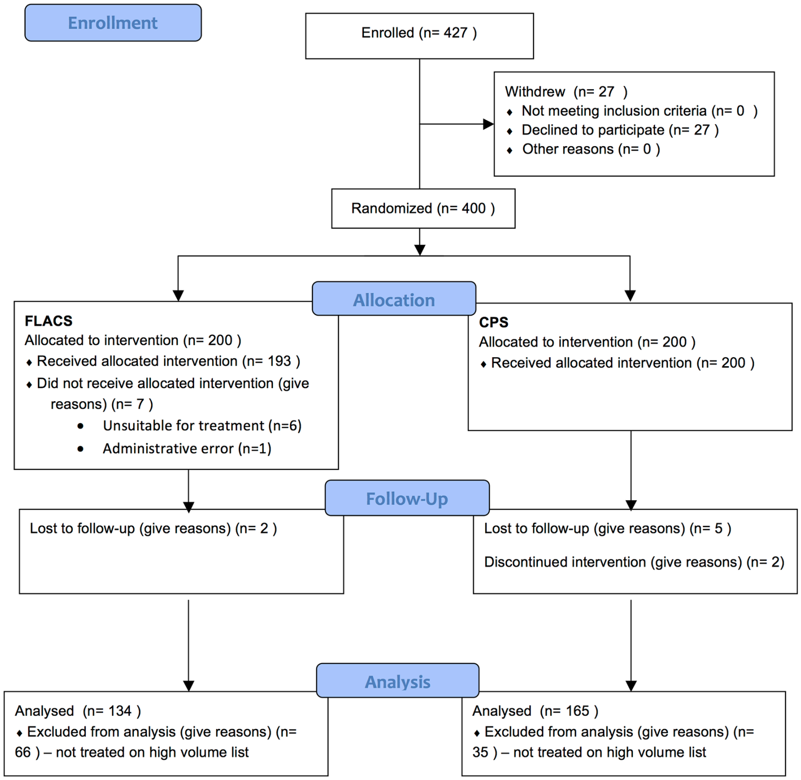

Figure 2 CONSORT flowchart of participant numbers through the study. FLACS, femtosecond laser-assisted cataract surgery .

Two hundred and ninety nine of the 400 cases were performed on designated high-volume theatre lists, where a hub-and-spoke FLACS model (with one FL and two ORs) was compared with independent CPS theatre lists. Details of operative timings and OR utilisation within these lists were recorded. Our aims were to provide the best quality evidence to date on whether FLACS can improve productivity in cataract surgery in the public health sector while maintaining safety and efficacy and what models of FLACS delivery might offset its associated addition costs.

METHODS

Randomised controlled trial

This analysis of relative productivity of FLACS delivered by hub-and-spoke model versus CPS was performed as a secondary outcome of a prospective randomised interventional case-controlled study at a single University Hospital (Guy's & St Thomas' Hospital NHS Foundation Trust, London, UK) to compare the clinical outcomes of FLACS with CPS (Clinicaltrials.gov registration number NCT02825693). This study adhered to the tenets of the declaration of Helsinki.

Patients were screened, recruited and consented from routine cataract clinics by members of the trial team (HR, VW) as per the trial protocol (V.2.0, 18 May 2016) (box 1).

Cataract surgery delivery models

General model, staff duties and patient flow

Cataract operations were performed during 4-hour theatre sessions. Patients for cataract surgery were admitted on a staggered arrival basis to an ophthalmic day care unit (ODCU) which staffed by a receptionist and a mixture of ophthalmic technicians (OTs) and ophthalmic nurses (ONs) (table 4).

After electronic registration by the receptionist, the patients were prepared for the OR by the ON/OTs. This included a series of medical observations, such as blood pressure and blood sugar (if diabetic), and administration of mydriatic therapy. Mydriatic therapy used in this study included a Mydriasert implant (Thea Laboratories, Clermont-Ferrand, France) and two drops of topical diclofenac sodium 0.1% to reduce the risk of intraoperative miosis.[12 13] The ward ON/OTs brought and collected the patients to and from the OR, which were adjacent to the ODCU, after being telephoned by one of the OR theatre nurses (TNs). After surgery was completed, the ON/OTs performed further medical observations, gave advice about aftercare, dispensed medication, discharged the patients and arranged follow-up.

Patients were treated on either all-FLACS or all-CPS theatre lists. All cataract operations were performed under local anaesthetic. All were unilateral and no other additional procedures

Table 1 Demographics of patients included and excluded from the hub-and-spoke model analysis demonstrating equivalence between the two groups

	High-volume theatre list participants	Patients not treated on designated high-volume theatre lists	P value
Male/female	140/159	41/60	0.30
First eye/second eye	243/56	87/14	0.29
Right eye/left eye	164/135	55/46	1
Age (years)	69.45±10.81	72.42±8.6	0.01
Preoperative best-corrected distance visual acuity (logMAR)	0.60±0.51	0.51±0.36	0.10
Spherical equivalent refractive error dioptrer (D)	−0.50±4.32	−0.38±3.52	0.80
Axial length (mm)	23.78±1.39	23.67±1.56	0.51
Anterior chamber depth (mm)	3.27±0.38	3.10±0.55	<0.01
Average predicted PCR risk[18]	1.63%±1.24%	1.63%±0.71%	1

PCR, posterior capsular rupture.

planned, other than arcuate keratotomies for reduction of corneal astigmatism.

The duties of the ophthalmologist inside the OR included helping positioning the patient on the operating table, the scribing of patient details onto the whiteboard, the removing of the Mydriasert implant, the marking of the forehead above the eye for cataract surgery prior to the WHO checklist,[14] scrubbing and gowning, leading the WHO checklist, preparation and draping of the eye for surgery, operating, writing the operation notes and scanning the paper WHO checklist into the hospital's electronic patient record software.

FLACS hub-and spoke delivery model

FLACS theatre lists were run as a hub-and-spoke model (figure 1). A LenSx FL (Alcon, Fort Worth, Texas, USA) was installed in the anaesthetic room of one of the ORs, hereafter referred to as the laser suite (LS), and was used to feed patients into two adjacent ophthalmic ORs which were running in parallel. The FL was operated by an ophthalmologist (HR, VW). The model required an additional OT who supervised patients waiting in the corridor outside the LS (table 4). There was a maximum of four patients seated in the theatre corridor at any one time (two patients waiting for laser treatment, two patients waiting to enter OR). In the FLACS model, the ophthalmologist performing the FL treatment was responsible for marking the patients' eyes before laser, delivering laser treatment, removing the Mydriasert implant and instilling additional topical phenylephrine 10%. Performing laser treatment included preparing the PI, entering patient details into the FL, selecting the planned treatment profile, positioning the patient on the laser bed, instilling topical anaesthetic in to the operative eye, inserting the lid speculum, docking the PI to the eye, performing optical coherence tomography of the anterior segment, choosing the treatment parameters and delivering the laser treatment. If completion of FL treatment was not possible for any reason, this and the reason why was recorded and the patient proceeded to the OR for CPS.

The number of patients booked to each 4-hour theatre list was decided in advance of each theatre list. The intention was to attempt to always maximise the number of patients treated during the allotted theatre time with reference to the levels of nursing and paramedical staffing. Initial targets were chosen based on existing experience of CPS and FLACS at our institution and titrated as the trial progressed, according to whether theatre lists were finishing early or overrunning.

OR timings

Two hundred and ninety nine of the 400 cases were performed on designated high-volume theatre lists, where patients were randomised to either hub-and-spoke FLACS model (with one FL and two ORs) or CPS only theatre lists. Various timings of OR utilisation were undertaken by a TN and included the time taken for the patient to enter the OR, duration of cataract surgery, time taken for the patient to exit the OR after completion of surgery, the total individual patient time in the OR, the time the OR was empty between patients, overruns and underruns of allotted OR time, and so on.

Timings of patient entry to the OR, start of operation, end of operation and patient exit from the OR were recorded contemporaneously by TNs using the existing theatre management software (Galaxy Theatre Management System, iSOFT, DXC Technology, Virginia, USA). Accuracy of timings was ensured by

Table 2 Patient demographics for the two treatment arms

	FLACS	CPS	P value
Male/female	62/72	78/87	0.90
First eye/second eye	111/23	132/33	0.55
Right eye/left eye	70/64	94/71	0.42
Age (years)	69.07±11.55	69.78±10.14	0.57
Preoperative best-corrected distance visual acuity (logMAR)	0.65±0.52	0.57±0.50	0.18
Spherical equivalent refractive error dioptrer (D)	−0.58±5.34	−0.42±3.15	0.75
Axial length (mm)	23.99±1.44	23.60±1.33	**0.02**
Anterior chamber depth (mm)	3.31±0.38	3.23±0.37	0.07
Average predicted PCR risk[18]	1.64%±0.99%	1.62%±1.43%	0.89

CPS, conventional phacoemulsification surgery; FLACS, femtosecond laser-assisted cataract surgery; PCR, posterior capsular rupture.

Table 3 Staffing levels associated with delivery of hub-and-spoke FLACS and CPS services

	FLACS (both ORs)	CPS (both ORs)
ORs		
Ophthalmologists	3	3
OR nurses	6.5	6.5
Ophthalmic day care unit		
Ophthalmic technicians	3	2
Ophthalmic nurses	2	2
Receptionist	1	1

CPS, conventional phacoemulsification surgery; FLACS, femtosecond laser-assisted cataract surgery; ORs, operating rooms.

Table 4 Comparison of OR timings (in minutes) between hub-and-spoke FLACS and CPS based on intention-to-treat analysis

	FLACS (n=139)	CPS (n=160)	t test (P value)
Time from entering OR to start of operation	5.83±2.58	6.25±2.91	0.19
Duration of operation	12.04±4.89	14.54±6.19	<0.001
Time from end of operation to exiting OR	2.47±0.66	2.6±1.02	0.20
Total time in OR	20.34±5.82	23.39±6.89	<0.001
OR empty	5.27±3.25	5.23±3.28	0.92

CPS, conventional phacoemulsification surgery; FLACS, femtosecond laser -assisted cataract surgery; OR, operating room.

a trained observer (IM). Timings of patient entry and exit from the LS were recorded by the ophthalmologist performing the laser treatment. Start of operation and end of operation were defined as application of antiseptic solution to the eye and skin, and removal of eyelid speculum. Because of the nature of the surgery, it was not possible to mask any of the surgical team to the treatment arm.

Economic model

The results from this were used as inputs for a hypothetical economic model, reported in a previous publication, to determine an estimation of the costs of cataract surgery.[11] This financial model has been described in greater detail in the previous publication but was based on averaged costs/values from five different NHS foundation trusts and four FL manufacturers. This model was used to provide an estimation of the difference in cost per case of running a FLACS service as compared with a traditional cataract service. Furthermore, if the results supported that a hub-and-spoke model could be run with more than two ORs, these iterations were also tested using the model.

Statistics

For the purposes of this study, the first two CPS and FLACS theatre lists each were excluded from analysis as they were scheduled with reduced patient numbers in order to allow theatre staff to familiarise with the models. The final four theatre sessions of the study were run as mixed lists in order to facilitate the scheduling of the remaining research participants and to avoid underused theatre sessions. These final mixed lists were also excluded from analysis.

Table 5 Comparison of OR timings (in minutes) between hub-and-spoke FLACS and CPS based on actual operation performed

	FLACS (n=134)	CPS (n=165)	t test (P value)	FLACS converted to CPS (n=5)
Time from entering OR to start of operation	5.82±2.62	6.24±2.87	0.19	6±1.58
Duration of operation	11.73±3.53	14.71±6.76	<0.001	20.40±17.87
Time from end of operation to exiting OR	2.47±0.66	2.59±1.02	0.24	2.4±0.89
Total time in OR	20.2±4.59	23.55±7.47	<0.001	28.8±19.33
OR empty	5.79±3.9	5.27±3.25	0.21	6.4±1.95

CPS, conventional phacoemulsification surgery; FLACS, femtosecond laser-assisted cataract surgery; OR, operating room .

The primary outcome as per the study protocol was the relative costs of FLACS and CPS. However, in light of inherent difficulties in accurate recordings of costs within a large tertiary ophthalmology service, it was determined that this would be replaced with the number of cases on FLACS and CPS lists and the duration of the operations. This current study of 299 patients had a power of 99% to detect an effect size (d) of 0.5 for the numbers of participants included in this analysis with regard to duration of surgery with $\alpha=0.05$ and a two-tailed analysis.

Baseline characteristics were summarised for each treatment arm. Results were analysed primarily as per intention to treat. Continuous data were reported using means and SD if data appear Gaussian, or medians and IQR if not. Binary data were reported as frequencies and percentages and evaluated with Fischer's exact test. Student's t-tests were used for parametric data and the Mann-Whitney U test for non-parametric. All statistical tests used a two-sided P value of $\alpha=0.05$ unless otherwise specified. Intraoperative complications were defined as any event that involved unintentional trauma to an ocular structure, requiring additional treatment or having a negative effect on participants' eyesight.

RESULTS

A total of 427 patients (427 eyes) were recruited for the study and randomised to receive FLACS or CPS. Twenty seven were excluded or withdrew in advance of surgery. For the purpose of this study comparing FLACS in a hub-and-spoke model with dual CPS theatre lists, 299 of 400 operations were included for analysis (figure 2). Excluded patients included 57 patients who had surgery on the first two of each theatre sessions for FLACS/CPS and 44 patients treated on mixed (CPS and FLACS) theatre lists. There were no significant differences between patients included and excluded for this analysis other than those excluded were on average 3 years older (P=0.01) and had shallower anterior chambers by 0.17 mm (P<0.01) (table 1). Of the 299 eyes included in this analysis, 134 patients had received FLACS and 165 patients underwent CPS. Baseline demographics for the FLACS and CPS groups are seen in table 2. The only significant difference at baseline was the FLACS group had a longer axial length by 0.39 mm (P=0.02). Five patients due to receive FLACS were treated with CPS due to the following reasons: palpebral aperture too narrow for PI (n=3, 2.2%), patient lack of compliance (n=1, 0.7%) and administrative error (n=1, 0.7%).

The 139 patients undergoing FLACS were treated during eight hub-and-spoke sessions, involving 16 4-hour theatre sessions. The 160 patients randomised to CPS were treated on 20 cataract theatre lists. The average OR utilisation of a hub-and-spoke session was 221±21 min (92.05%±8.71) with a median of nine patients treated in each OR, while the average duration of a CPS list was 230±22 min (95.81%±9.17) (P<0.001) with a median of eight patients treated per list. Patients receiving FLACS spent, a mean time of 5.85±1.99 min in the LS. Twenty-five per cent of FLACS theatre sessions overran the allotted 4 hours compared with 30% of CPS lists. Average theatre overrun was 5±2.16 min for FLACS and 13.67±8.76 min for CPS (P=0.09).

Staffing levels for both models can be seen in table 3. The hub-and-spoke model required one additional OT to be present compared with the CPS. A comparison of the average times associated with each operation can be seen in tables 4 and 5.

Complications

The overall rate of intraoperative complications was similar between the two groups 3.54% vs 3.76%; however, there was

Table 6 Incidence of complications between the two treatment arms based on intention-to-treat analysis

Complications	FLACS	CPS	RR	P value
Anterior capsular tear	3 (2.16%)	3 (1.88%)	1.15 (95% CI 0.24 to 5.6)	0.86
Posterior capsule tear with vitreous loss	0 (0%)	3 (1.88%)	0.16 (95% CI 0.01 to 3.15)	0.23
DM tear	1 (0.72%)	0 (0%)	3.45 (95% CI 0.14 to 84.0)	0.45
Suprachoroidal haemorrhage	1 (0.72%)*	0 (0%)	3.45 (95% CI 0.14 to 84.0)	0.45
Abandoned-extreme zonular weakness	0 (0%)	1 (0.63%)	0.38 (95% CI 0.01 to 9.34)	0.56
Total complication rate	3.54%	3.76%	0.95 (95% CI 0.30 to 3.07)	0.94

*This patient was allocated to FLACS but was unable to undergo this procedure and the patient underwent CPS.
CPS, conventional phacoemulsification surgery; DM, Descemet's membrane; FLACS, femtosecond laser-assisted cataract surgery; RR, relative risk.

a noticeable difference in the rates of vitreous loss (0% with FLACS compared with 1.88% in CPS) (table 6).

Economic modelling

Based on our OR timings, using a hub-and-spoke model, we achieved a mean reduction of total time in the OR per patient of 3.05 min. This allowed us to undertake one extra FLACS case per 4-hour theatre list compared with our CPS only lists. The average number of cases on using our operative models was 8 for CPS and 9 for FLACS, which represented an average 12.5% increase in productivity. We applied these results to our economic model. Based on these results, the average cost for each cataract operation was £355.42 for CPS and £500.02 for FLACS (figure 3).

A bivariate sensitivity analysis examining the number of cases/week and the cost of the PI was performed, reporting the additional cost per case of a FLACS service (table 7).

3:1 and 4:1 hub-and-spoke model

Although the duration of FL application to the eye is usually between 25 and 45 s, patient time inside the laser room was 5.85±1.99 min. In our model, the laser operator is an ophthalmologist working unassisted, and therefore the majority of time spent is on preparing the patient and setting up the laser. Based on our results, we recommend that the maximum number of ORs which could be run (in order to maximise the utility of an FL) in a hub-and-spoke model would be 4 (average total patient time in OR +turnaround time 25.12±5.25 min). Adding a third OR to our economic modelling of the costs of cataract surgery reduced the cost per case from £500.02 to £477.28 and adding a fourth reduced it to £465.91. Performing the same bivariate analyses on a 3:1 and 4:1 hub-and-spoke models as above shows that the difference in cost could be reduced further if the hospital was performing greater numbers of cataract surgery and received a significant discount in the cost of the PI from the manufacturer (table 8). However, in order to break even, our financial modelling shows the manufacturers would need to offer between 78% and 99% discount on the cost of the PIs (table 9).

Cases unable to undergo FLACS

Five (3.6%) patients randomised to FLACS did not receive FL treatment. This is consistent with reported rates of unsuccessful attempts at FLACS between 2.3% and 6.3%.[15–17] In our experience, the most common reason was that the palpebral aperture was too narrow to permit the 16 mm PI to applanate with the cornea. Four of these patients underwent uneventful CPS, with one suffering a suprachoroidal haemorrhage. This patient was considered at increased risk for this rare complication with an axial length of 19.66 mm.

DISCUSSION

We have conducted a large RCT comparing FLACS with CPS by reporting the clinical outcomes and testing the efficiency of FL-centric methods of running cataract theatre lists. When FLACS is performed within traditional models featuring one surgeon, or installing the FL in the OR, productivity may be adversely affected, leading to incurring additional indirect costs.[8–10] This is because the duration of the patient's experience is increased with FLACS compared with CPS (time in OR+LS=26.05 for FLACS vs 23.55 for CPS). Evaluating new models of delivering cataract surgery (such as a hub-and-spoke model) within a RCT, where patients are prospectively randomised to CPS or FLACS, allows us to test the model within a rigorous framework, rather than performing a case–control study where bias may be inherent.

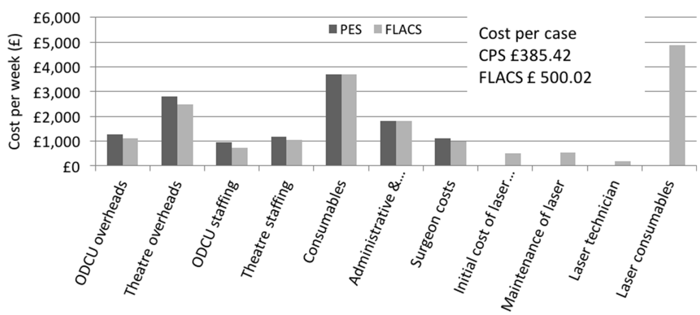

Figure 3 Comparison of weekly costs of FLACS vs CPS services. CPS, conventional phacoemulsification surgery; PES, phacoemulsification surgery; FLACS, femtosecond laser-assisted cataract surgery; ODCU, ophthalmic day care unit.

Roberts HW, *et al*. *Br J Ophthalmol* 2018;**0**:1–8. doi:10.1136/bjophthalmol-2017-311319

Table 7 Bivariate sensitivity analysis comparing effects of cost of patient interface and number of operations performed per week on the additional cost of FLACS compared with CPS within a 2:1 hub-and-spoke FLACS model

Cost per laser patient interface (£)	Number of cataract operations performed per week			
	20	40	60	80
40	£72.75	£46.51	£37.76	£33.39
70	£102.75	£76.51	£67.76	£63.39
100	£132.75	£106.51	£97.76	£93.39
130	£162.75	£136.51	£127.76	£123.39

CPS, conventional phacoemulsification surgery; FLACS, femtosecond laser-assisted cataract surgery .

By deploying an FL in the anaesthetic room adjacent to the OR and using a hub-and-spoke model, we have found that surgical time and patient time in OR are shorter for FLACS than CPS. Transferring some of the surgical steps into the LS reduces patient time in OR by 3.05 min for FLACS ($P<0.001$) led to an average of one extra operation per OR operating list of FLACS (median nine cases per list) than CPS (median eight cases per list), resulting in a 12.5% improvement in productivity (overall two more operations per session). Furthermore, despite the additional cases, the FLACS lists were shorter than the CPS lists, and more CPS sessions overran. Our method of titrating the numbers of patients scheduled for surgery to maximise the number of operations within the 4-hour session resulted in extremely high levels of OR utilisation. Our ambition resulted in a number of theatre sessions overrunning (25% FLACS vs 30% CPS), especially when unforeseen complications had occurred. Theatre list overruns may incur financial penalty at some NHS/public hospitals; however, our greater concern was to test the limits of our models.

There were some differences between the 299 patients included for this analysis and the 101 excluded, namely that the excluded group were 3 years older on average, with a corresponding shallower anterior chamber depth (ACD) by 0.17 mm. It is unlikely that these differences are clinically significant and would have had a material effect on the timings of the theatre list.[18] Importantly, the prospectively calculated risk of posterior capsular rupture (PCR) was equivalent between the two groups.

Table 8 Bivariate sensitivity analyses demonstrating the additional cost of FLACS compared with CPS within a theoretical 3:1 and 4:1 hub-and-spoke FLACS model when the cost of the patient interface and the number of operations per week are varied

Cost per patient interface	Number of operations performed per week			
	40	60	80	100
3 : 1 model				
40	£33.40	£24.65	£20.28	£17.65
70	£63.40	£54.65	£50.28	£47.65
100	£93.40	£84.65	£80.28	£77.65
130	£123.40	£114.65	£110.28	£107.65
4 : 1 model				
40	£26.84	£18.10	£13.72	£11.10
70	£56.84	£48.10	£43.72	£41.10
100	£86.84	£78.10	£73.72	£71.10
130	£116.84	£108.10	£103.72	£101.10

CPS, conventional phacoemulsification surgery; FLACS, femtosecond laser-assisted cataract surgery.

Table 9 Break even points for hub-and-spoke FLACS with CPS services calculated for the % discount of the PI based on the number of ORs concurrently run and the number of operations performed per year

% discount on cost of PI	Number of cataract operations/year				
	2000	3000	4000	5000	6000
4:1 model	91	84	81	79	78
3:1 model	96	89	86	84	82
2:1 model	n/a	99	95	93	92

CPS, conventional phacoemulsification surgery; FLACS, femtosecond laser-assisted cataract surgery; OR, operating room; PI, patient interface.

The mean time of each patient undergoing patient preparation for FL and FL application was 5.85±1.99 min. Based on such results, it is easily possible to have a hub-and-spoke model of one FL feeding into three or four ORs (4:1 or 3:1) rather than two (2:1). We recommend that the ideal number of ORs to maximise the utility of an FL in a hub-and-spoke model would be 4 (average total time per patient in OR +turnaround 25.12±5.25 min). We predict that this would result in three or four more operations performed overall by the FLACS model per session (one for each OR).

Potential issues of having a 3:1 or 4:1 model to attempt to use an FL as a tool for high-volume surgery is that this requires a suitable and dedicated room within theatres and multiple ORs. This limits the use of such a model to an institution with such facilities already in place or a purpose-built unit (thus incurring additional costs). For instance, with a maximum of two eye ORs at our institution we are not able to evaluate adding additional ORs to our existing hub-and-spoke model. It is important to incorporate any development costs in the planning process if deciding whether to adopt this technology.

In order to minimise costs of running the hub-and-spoke model, it is important to minimise the additional number of staff needed. Our model required two additional members of staff, one ophthalmologist to operate the laser and one OT to chaperone the patients between the LS and ORs. For our CPS lists, the extra OT was not present; however, there were three ophthalmologists between the two ORs. This may have improved the efficiency of the CPS lists in our study to a degree by allowing the surgeons to rotate. The cost of the third surgeon was included in the financial modelling for the CPS model so as not to bias the model further in favour of CPS. In the FLACS model, it was also possible to permit surgeon rotation between the ophthalmologists performing laser and operating, thus possibly reducing the risk of surgeon fatigue during high-volume cataract surgery.

In a previous publication we performed hypothetical financial modelling of hub-and-spoke delivered FLACS. Using a 2:1 model, we found using bivariate sensitivity analyses that a 43% improvement in productivity would need to be achieved and accompanied by a 52% discount on the PI for the service to break even. This improvement in productivity was not realised by our study with a time saving of 3 min per patient (in the OR). The financial model demonstrates that the PI is the single most expensive item for the FLACS service. However, thus far FL platforms have tended to be used, and marketed as a premium product (based on reported improved refractive outcomes and stability).[19] However, it is very likely that a public healthcare service may be able to negotiate discounts on the costs of FLACS, especially if used within a high-volume service (which further improves affordability) (tables 7 and 8). Further cost savings may be made by improved safety which may make cost savings in postoperative management.[20] It is important to note therefore that while there was no difference in PCR and vitreous loss rates in this arm of this study to investigate comparative high-volume hub-and-spoke FLACS and CPS theatres lists (table 6), the results of the overall RCT showed a statistically significant reduction in PCR with FLACS, in a public health setting with different grade of surgeons operating, including those in training (H. Roberts, D. O'Brart, personal communication, 2018). As such complications incur additional costs, if our findings with respect to PCR rates are replicated by others, then our economic modelling might be more favourably inclined towards a FLACS hub-and-spoke model.

A previous time and motion study (TMS) investigating the effects of number of allied health professionals (AHPs) assisting in cataract theatre lists on the overall productivity showed a marked difference in the number of cataract surgeries performed between different institutions. Furthermore, a minimum of four AHPs may be required to deliver high-volume cataract surgery with effective use of theatre time and minimum delays.[21] Our cataract ORs are generally run with three AHPs, which precludes further increases in productivity, which is evident in our turnaround time compared with other surgical units. The average time between one operation finishing and the start of the next was 13.57 and 14.08 min for FLACS and CPS, respectively, meaning that only between 47.0% and 50.8% of OR time is spent engaged in surgery. Our previous TMS showed that patient turnover in NHS units with four AHPs present can be reduced to 5.4 min from one operation ending to the next starting. Including one additional AHP per OR to our unit (at a cost of £70 per session) to facilitate patient turnover could provide a similar overall time saving as this FL technology.

Limitations

We chose to consider the productivity difference in terms of number of operations per OR and found a 12.5% improvement in FLACS. However, other methods of assessing productivity could have been chosen (eg, number of cases per surgeon). However, there are usually an abundance of cataract surgeons in a department compared with theatre time and space, making this more of a limiting factor. We did not incur any infrastructure costs in the installation of the laser into the anaesthetic room and so are unable to provide a representation of infrastructure costs into our model. We understand however that other surgical units have incurred significant costs during the installation of an FL, so this is an important consideration. The surgical team was not masked to the treatment arms and this may be associated with performance bias. Another potential source of bias is that we had to book patients to theatre lists preemptively; having a busier list may have improved productivity. Nevertheless, we aimed to combat this by a fair and transparent method of a run in period before the trial commenced to build experience with the model and titrating booking numbers depending on previous early finishes and overrunning. These potential biases may have been even more evident within a case–control study, hence why an RCT methodology was preferred.

CONCLUSION

FLACS with a hub-and-spoke model was significantly faster than CPS, with patients spending less time in the OR. This enabled a slight improvement in productivity, but not sufficient to meaningfully offset the additional costs relating to FLACS. Further gains in productivity may have been achieved with a 3:1 or 4:1 hub-and-spoke model.

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Evaluation of a hub-and-spoke model for the delivery of femtosecond laser-assisted cataract surgery within the context of a large randomised controlled trial

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ARTICLE

Refractive outcomes after limbal relaxing incisions or femtosecond laser arcuate keratotomy to manage corneal astigmatism at the time of cataract surgery

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Purpose: To compare the results of manual limbal relaxing incisions (LRIs) performed during conventional phacoemulsification surgery with those of nonpenetrating femtosecond laser arcuate keratotomies performed during femtosecond laser–assisted cataract surgery to manage corneal astigmatism.

Setting: Guy's and St. Thomas' NHS Foundation Trust, London, United Kingdom.

Design: Randomized case-controlled trial.

Methods: This was a secondary outcome of a randomized controlled trial comparing 400 patients treated with conventional phacoemulsification surgery or femtosecond laser–assisted cataract surgery. All patients with corneal astigmatism greater than 0.9 diopter (D) were offered LRIs or femtosecond laser arcuate keratotomy based on the original randomization. Visual acuity, postoperative refraction, and corneal topography were recorded 4 weeks postoperatively. Vector analysis was performed using the Alpins method.

Results: Fifty-one eyes of 51 patients received LRIs, and 53 eyes of 53 patients received femtosecond arcuate keratotomies. The mean target induced astigmatism was 1.50 D and 1.38 D, respectively, with 1.02 D and 1.23 D surgically induced astigmatism ($P = .21$), resulting in the femtosecond arcuate keratotomy group having a smaller difference vector (1.17 D versus 0.89 D; $P = .02$) and a greater correction index (0.48 versus 0.73; $P = .02$). Forty-four percent of patients in the femtosecond arcuate keratotomy group and 20% in the LRI group attained a postoperative cylinder of less than 0.50 D ($P = .01$).

Conclusions: The femtosecond arcuate keratotomy group achieved a higher correction index and a smaller difference vector. The femtosecond arcuate keratotomy patients showed less postoperative cylinder than LRI patients.

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Corneal astigmatism in patients having cataract surgery is common, with approximately 40% of patients having more than 1.0 diopter (D) and 10% more than 2.0 D of corneal astigmatism.[1] Various techniques have been introduced to decrease corneal astigmatism at the time of cataract surgery and thus reduce postoperative spectacle dependence and maximize uncorrected distance visual acuity (UDVA). These include on-axis incisions supplemented with opposite clear corneal incisions if indicated, limbal relaxing incisions (LRIs), femtosecond laser arcuate keratotomies, toric intraocular lenses (IOLs), and refractive surgery after cataract surgery (bioptics).[2–6]

Limbal relaxing incisions or femtosecond arcuate keratotomies have been found to be efficacious in the management of low to moderate astigmatism (<2.5 to 3.0 D) but are less suitable for moderate to high astigmatism, which requires toric IOLs or bioptics.[7,8] To our knowledge, there are no trials comparing the effectiveness of LRIs with that of femtosecond arcuate keratotomies in the management of low-to-moderate corneal astigmatism at the time of cataract surgery. The purpose of this study was to determine

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whether there are differences between laser-delivered and manually delivered keratotomies using vector analysis.[9–12]

PATIENTS AND METHODS

This analysis of refractive outcomes of patients treated with LRIs or femtosecond arcuate keratotomies was performed as a secondary outcome of a prospective randomized interventional case-controlled study at Guy's and St. Thomas' Hospital NHS Foundation Trust, London, United Kingdom. The study was approved by local Research and Development and Cambridge South Research Ethics Committee (reference 16/EE/0180). This study adhered to the tenets of the Declaration of Helsinki.

Specific to this subgroup analysis, any patient with corneal astigmatism greater than 0.9 D based on Scheimpflug tomography (Pentacam, Oculus Optikgeräte GmbH) were offered LRIs or femtosecond arcuate keratotomy as part of their cataract operation based on the initial randomization. Eyes with previous refractive or corneal surgery or corneal pathology were excluded. Partial coherence interferometry (PCI) (IOLMaster 500, Carl Zeiss Meditec AG) was performed to obtain keratometry (K) measurements for IOL formula calculation. Corneal astigmatism was measured using Scheimpflug tomography, and the measurements were used for preoperative astigmatism planning and postoperative analysis. When biometry was not possible on PCI because of the density of a cataract, A-scan ultrasound biometry (Carl Zeiss Meditec AG) was performed. All postoperative results were recorded at the 4-week follow-up.

Surgical Technique

The methods of the study are described in the publication of the main study findings.[A] Eyes were randomized to receive femtosecond laser–assisted cataract surgery or conventional phacoemulsification surgery. Manual limbal markings at 0 degree and 180 degrees were made on all eyes preoperatively with patients a sitting position at the slitlamp. For the markings, a needle was used scratch the corneal epithelium at the limbus; this was followed by the use of a sterile marker pen.

Femtosecond laser–assisted cataract surgery was performed using the Lensx femtosecond laser (Alcon Surgical, Inc.). The femtosecond laser was used to create the capsulotomy and fragment the lens in all patients and intrastromal femtosecond arcuate keratotomy was performed when appropriate. All cataract surgeries were performed using local anesthesia. After the femtosecond laser treatment, the patient was transferred to the operating room for the remainder of the cataract extraction. Phacoemulsification was performed using the Infiniti machine (Alcon Surgical, Inc.) in both groups. Patients having conventional phacoemulsification surgery were prepared for surgery in the same way as those in the laser arm. Instead of receiving laser pretreatment, they were brought straight to surgery and received LRIs at the start of the cataract operation. All operations were performed by experienced surgeons who had completed at least 30 femtosecond laser–assisted cataract surgery procedures (H.W.R., V.K.W., D.P.S.O.).

Limbal Relaxing Incision Group Limbal relaxing incision parameters were calculated based on Donnenfeld's nomogram via an online software program[B] based on the K readings from the Scheimpflug tomographer and the individual surgeon's surgically induced astigmatism (SIA) values. Target induced astigmatism (TIA) was always aimed at 100% correction. Paired arcuate LRIs were always performed; when the surgeon's preference was to operate on axis, the 2.4 mm main wound was positioned in the middle of the LRI. When anatomy or comfort dictated an off-axis approach, the surgeon's SIA was used to modify the LRIs.

A Mendez-style ring was used to mark the steep meridians at the start of the surgery. The LRI incision was made before the commencement of phacoemulsification using a 2.4 mm keratome to incise through epithelium and Bowman layer. Next, a 600 μm guarded diamond knife was used to incise through the stroma. No corneal sutures were placed during the surgery.

Femtosecond Arcuate Keratometry Group Femtosecond arcuate keratotomy parameters were determined by a nomogram previously reported by Day et al.[7] The settings of the femtosecond laser for the arcuate intrastromal incisions were also maintained. Although this nomogram was intended to achieve up to 70% correction only, for ease of interpretation of outcome data, the TIA was defined as a 100% correction with no residual postoperative corneal astigmatism. After the femtosecond laser was docked, the horizontal meridian was manually adjusted in cases of cyclorotation.[13] In cases in which either of the arcuate keratotomies overlapped with the surgeon's planned manual wound, the main section was positioned more peripherally than the arcuate keratotomy so that it would not be involved.

Statistical Analysis

Baseline characteristics were summarized for each treatment arm. Results were analyzed primarily as per intention to treat. For all evaluations of visual acuity as an outcome, patients with visually significant ocular comorbidities were excluded prospectively and those opting for a refractive target other than emmetropia were excluded from analysis of refractive outcome. Snellen visual acuities were converted to logarithm of the minimum angle of resolution notation for analysis.[14] Comparative and descriptive statistical analyses included the Fisher exact test, chi-square test, and Student *t* tests. All statistical tests used a 2-sided *P* value of α equal to 0.05 unless otherwise specified. Excel software (Microsoft Corp.) was used for data entry, analysis, and graphic representation. Intraoperative or postoperative complications were defined as any event that involved unintentional trauma to an ocular structure, requiring additional treatment, or having a negative effect on the patient's eyesight.

Analysis of corneal astigmatic outcomes based on corneal topography measurements before and after surgery was performed using the Alpins method,[9–11] with calculation of the 3 following vector parameters: TIA, SIA, and difference vector. Results are presented based on the standardized graphs for reporting the outcomes of refractive surgery and IOL-based refractive surgery.[12,15] Additional parameters calculated included the correction index, coefficient of adjustment, magnitude of error, angle of error, and index of success. The axis of the steep meridian was used throughout.

RESULTS

Four hundred twenty-seven patients were recruited to the study between August 2016 and June 2017 as per the inclusion and exclusion criteria. Twenty-seven patients withdrew from the trial before surgery. Four hundred eyes of 400 patients received surgery between November 2016 and June 2017 (200 conventional phacoemulsification surgery; 200 femtosecond laser–assisted cataract surgery).

Fifty-one eyes of 51 patients in the conventional phacoemulsification group received LRIs, of which 8 were excluded from the UDVA analysis because of visual comorbidities (6 age-related macular degeneration [AMD], 1 amblyopia, and 1 chronic central serous chorioretinopathy). Fifty-three eyes of 53 patients in the femtosecond laser–assisted cataract surgery group received femtosecond arcuate keratotomy, of which 9 were excluded for visual comorbidities (4 AMD, 2 amblyopia, 1 previous retinal detachment, 1 vitreomacular traction, and 1 central retinal vein occlusion).

Table 1 shows the patients' demographics and preoperative values. At baseline, the corrected distance visual acuity (CDVA) was statistically significantly worse (by 12 letters) and axial length (AL) statistically significantly longer (by 0.7 mm) in the femtosecond group. Figures 1 and 2 show the TIA and SIA single-angle vector plot. The SIA was less than TIA in both groups, indicating undercorrection. However, the femtosecond arcuate keratotomy corrected more astigmatism than the LRI, as shown by the correction indices (P = .02) (Table 2). The difference vector was also lower in the femtosecond arcuate keratotomy group (P = .02), indicating better correction (Table 2 and Figures 3 and 4). Despite a greater SIA, higher correction index, and lower difference vector in the femtosecond group, there was not quite a statistically significant difference in the index of success (ratio of difference vector to TIA) between the 2 groups (P = .07). Figures 5 and 6 show the angles of error and the TIA versus SIA graphs.

Figures 7 to 10 show the 4 standard graphs for representation of refractive outcomes of cataract surgery. In both groups, nearly 60% of patients (arcuate keratotomy 25/43; LRI 24/41) attained their visual potential without requiring refractive correction (Figure 8). Eight LRI patients (20%) and 18 femtosecond arcuate keratotomy patients (44%) attained a postoperative cylinder of less than 0.50 D (P = .01) and 18 patients (44%) versus 32 patients (74%) had less than 1.00 D of cylinder (P = .003) (Figure 10). The mean corneal astigmatism was reduced from 1.38 ± 0.40 D to 0.89 ± 0.54 D in the femtosecond arcuate keratotomy group and from 1.50 ± 0.46 D to 1.17 ± 0.69 D in the LRI group (P = .02). The postoperative refractive cylinder was 0.90 ± 0.50 D and 1.18 ± 0.90 D, respectively (P = .05). The arithmetic mean of the angle of error was very small in both groups, indicating neither group had overall misalignment of treatment. However, the absolute mean indicates a misalignment of 18 to 22 degrees (P = .28) (Table 2).

Femtosecond laser treatment was delivered successfully in all cases. There was a complication relating to laser delivery in 5 cases (9.4%) (corneal abrasion in 2 cases [3.7%] and incomplete capsulotomy in 3 cases [5.6%]). The femtosecond laser was not used to create any corneal incision. In all cases, it was used for capsulotomy creation, lens fragmentation, and arcuate keratotomy creation Limbal relaxing incisions were performed in the conventional phacoemulsification surgery group in all cases. None of the femtosecond arcuate keratotomies or LRIs resulted in complications, including posterior perforation or inadvertent placement. Intraoperatively, 2 patients in the femtosecond arcuate keratotomy group sustained an anterior capsule tear and 1 patient had intraoperative floppy-iris syndrome (IFIS). Two patients in the LRI group had IFIS and 1 had iris prolapse/trauma. Postoperatively, no patient in the LRI group had complications; 2 patients in the femtosecond arcuate keratotomy group had cystoid macular edema and 1 had a steroid response leading to an intraocular pressure of 30 mm Hg at 4 weeks.

DISCUSSION

The femtosecond laser can perform, with reliability and reproducibility, several steps of cataract surgery. These include the creation of arcuate keratotomies, which are performed to reduce corneal astigmatism at the time of surgery. Although the effects of laser capsulotomy on IOL centration and refraction as well as the effects of lens fragmentation on total phacoemulsification energy have been reported, this is the first study to assess the efficacy of automated femtosecond arcuate keratotomies compared with manual LRIs during cataract surgery. Both techniques have been shown to be efficacious at reducing corneal astigmatism but have not yet been directly compared.[7,16]

In this study, we used the femtosecond arcuate keratotomy nomogram originally described by Day et al.,[7] notwithstanding 2 important differences. First, we used a different femtosecond laser platform and second, unlike the study of Day's group, in which the main incisions were consistently temporal, we elected to perform our main incisions on axis when possible (eg, accounting for surgical access). Using

Table 1. Preoperative patient demographics and baseline values.

Parameter	LRI	Femto AK	*P* Value
Mean age (y)	72.5 ± 10.5	69.7 ± 12.0	.21
Female sex (%)	56.8	41.5	.24
Right eyes (%)	55.0	53.8	1.0
Mean CDVA (logMAR)	0.45 ± 0.38	0.69 ± 0.52	.01
SE refractive error (D)			
Arithmetic mean	0.81 ± 2.88	−1.40 ± 4.51	.004
Absolute mean	2.69 ± 2.48	3.25 ± 3.24	.32
Cylindrical refractive error (D)	−1.42 ± 0.79	−1.34 ± 0.99	.65
Axial length (mm)	23.56 ± 1.37	24.26 ± 1.69	.02
Mean corneal keratometry (D)	44.42 ± 1.33	43.98 ± 1.59	.13
Mean corneal astigmatism (D)*	1.50 ± 0.46	1.38 ± 0.40	.16
Summated vector mean	0.31 × 160	0.21 × 174	—

Means ± SD
CDVA = corrected distance visual acuity; corneal keratometry = maximum keratometry; Femto AK = femtosecond laser arcuate keratotomy; logMAR = logarithm of the minimum angle of resolution; LRI = limbal relaxing incision; SE = spherical equivalent
*Keratometry difference/target induced astigmatism vector

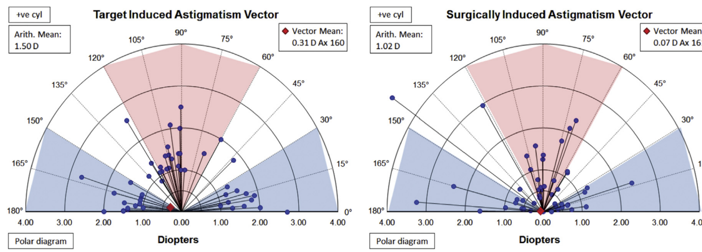

Figure 1. Single-angle polar plots regarding corneal astigmatism for TIA and SIA of patients treated with LRIs (+ve cyl = positive cylinder; Arith. = arithmetic; Ax = axis; LRI = limbal relaxing incisions; SIA = surgically induced astigmatism; TIA = target induced astigmatism).

this methodology, we found that femtosecond arcuate keratotomy had a greater correction index than LRIs, indicating that the SIA was 73% of the TIA (compared with 48% for LRIs). For analysis, the TIA in the femtosecond arcuate keratotomy group was assumed to be a 100% correction; however, the nomogram for femtosecond arcuate keratotomy aims for a 70% correction to avoid too many patients being overcorrected.[7] Thus, the femtosecond AK was very accurate in what it aimed to deliver. It might be assumed, therefore, that aiming for a 100% correction with femtosecond arcuate keratotomy with on-axis incisions might deliver better astigmatic correction than our results and should be the subject of further clinical studies and nomogram refinement.

Further areas for refinement include the accuracy of the femtosecond laser incisions, a better understanding of corneal biomechanics in the context of femtosecond arcuate keratotomies, and the effects of the femtosecond arcuate keratotomy on the posterior corneal curvature. A recent optical coherence tomography study of femtosecond arcuate keratotomies[17] showed that the midpoint depth of the intrastromal incisions was significantly more anterior than the planned parameters and that the locations of the paired intrastromal incisions in each eye were not correlated. In studies of biomechanical properties and factors contributing to outcomes of femtosecond arcuate keratotomy[18,19] the type of astigmatism (against-the-rule, with-the-rule, or oblique) were independent predictors of the efficacy of femtosecond arcuate keratotomy and corneal hysteresis had a negative correlation with the SIA at 1 to 6 months. Löffler et al.[20] found that femtosecond arcuate keratotomies affected the anterior corneal curvature and total corneal refractive power, but not the posterior curvature.

In our study, there were no significant differences in the absolute or arithmetic mean angle of error. This implies that the femtosecond laser arcuate keratotomies were no better aligned than what can be achieved manually. The femtosecond arcuate keratotomy group had a significantly smaller mean difference vector (the residual correction required to achieve the TIA), and yet the index of success was not quite statistically significant between the 2 groups. The index of success is defined as the difference vector divided by the TIA, where a number closer to zero indicates greater success, and the value in the LRI group was 0.81 compared with 0.65 in the laser group ($P = .07$). This could

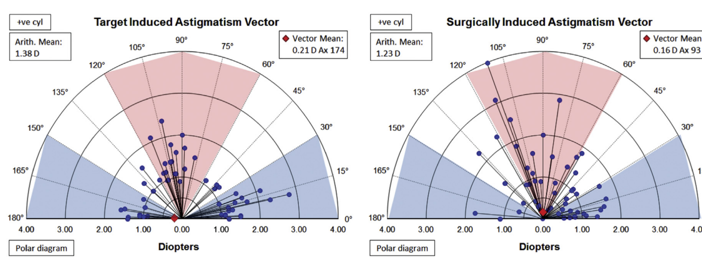

Figure 2. Single-angle polar plots regarding corneal astigmatism for TIA and SIA of patients treated with femtosecond laser arcuate keratotomies (+ve cyl = positive cylinder; Arith. = arithmetic; Ax = axis; LRI = limbal relaxing incisions; SIA = surgically induced astigmatism; TIA = target induced astigmatism).

Table 2. Vector analysis of postoperative results.

Parameter	Group				*P* Value
	LRI		Femto AK		
	Mean	SD	Mean	SD	
TIA vector (D)					
Arithmetic mean	1.50	0.46	1.38	0.40	.16
Summated vector mean	0.31 × 160		0.21 × 174		
SIA vector (D)					
Arithmetic mean	1.02	0.91	1.23	0.77	.21
Summated vector mean	0.07 × 161		0.16 × 93		
Correction index					
Geometric mean	0.48	0.57	0.73	0.49	.02
Difference vector (D)					
Arithmetic mean	1.17	0.69	0.89	0.54	.02
Summated vector mean	0.25 × 160		0.37 × 178		
Index of success					
Geometric mean	0.81	0.49	0.65	0.4	.07
Angle of error (degrees)					
Arithmetic mean	−3.35	29.90	2.35	25.95	.30
Absolute mean	22.10	20.19	17.99	18.69	.28

Femto AK = femtosecond laser arcuate keratotomy; LRI = limbal relaxing incision; SIA = surgically induced astigmatism; TIA = target induced astigmatism

therefore possibly be explained by TIA in the LRI group being 0.12 D greater.

In addition to our findings that femtosecond arcuate keratotomy had a greater correction index than LRI, we found several possible several advantages of femtosecond arcuate keratotomies over LRIs. First, they take a few seconds to program into the laser platform and for the laser platform to undertake them. In addition, although in this study we marked all eyes at the slitlamp preoperatively, several femtosecond laser–assisted cataract surgery platforms now allow integration with corneal topography and/or tomography devices and provide iris or conjunctival vessel recognition. Thus, preoperative marking of the axis is becoming redundant,[13] enhancing patient and surgeon convenience. Finally, because the incisions are intrastromal, postoperative patient discomfort might be less than with LRIs and the chance of posterior or full-thickness perforation, infection, or inflammation might be lower. However, femtosecond laser technology has significant associated additional costs, and only limited additional cost and materials are required to perform arcuate keratotomies.

One key limitation of this study is that follow-up was limited to the first postoperative month and that longer term efficacy was not evaluated. The published literature reports variable results in terms of the regression of the effects of LRIs with time, although in general such corrections appear to be relatively stable after the first postoperative month.[21] In a series of 263 patients by Day et al.,[22] of which 87 had intrastromal arcuate keratotomies, the regression in

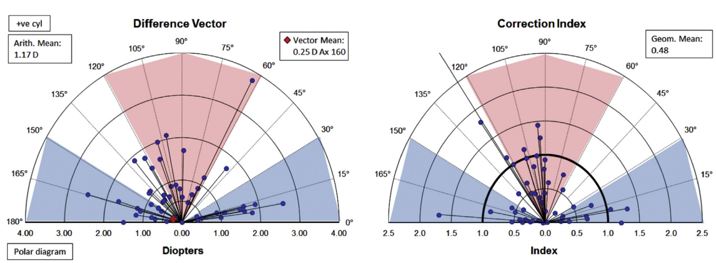

Figure 3. Single-angle polar plots regarding corneal astigmatism for difference vector and correction index (SIA) of patients treated with LRIs. One outlier is not represented on the correction index graph; the correction index of 3.38 is off the scale of the chart (at 60 degrees) (+ve cyl = positive cylinder; Arith. = arithmetic; Ax = axis; Geom. = geometric; LRIs = limbal relaxing incisions; SIA = surgically induced astigmatism).

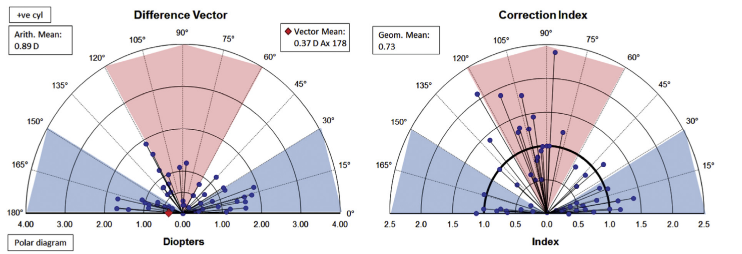

Figure 4. Single-angle polar plots regarding corneal astigmatism for difference vector and correction index (SIA) of patients treated with femtosecond laser arcuate keratotomies (+ve cyl = positive cylinder; Arith. = arithmetic; Ax = axis; Geom. = geometric; SIA = surgically induced astigmatism).

SIA was only 0.1 D between 1 month and 6 months and was equivalent between groups that did or did not receive arcuate keratotomies. Similarly, Chan et al.[6] found stability of the astigmatic correction by arcuate keratotomy between 2 months to 2 years postoperatively, and Byun et al.[19] found no significant changes between 2 months and 6 months and a series of 89 eyes. This suggests that astigmatic corrections achieved at 1 month are a good indicator of efficacy, although we are following our patients at 12 months to assess the longer term efficacy.

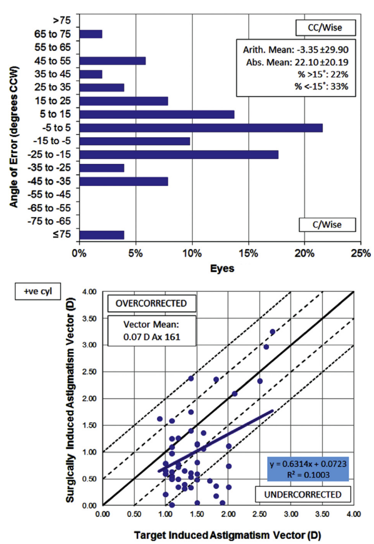

Figure 5. Astigmatism angles of error and the TIA versus SIA graphs of patients treated with LRIs (Abs. = absolute; Arith. = arithmetic; Ax = axis; CCW = counterclockwise; CC/Wise = counterclockwise; C/Wise = clockwise; LRIs = limbal relaxing incisions; SIA = surgically induced astigmatism; TIA = target induced astigmatism).

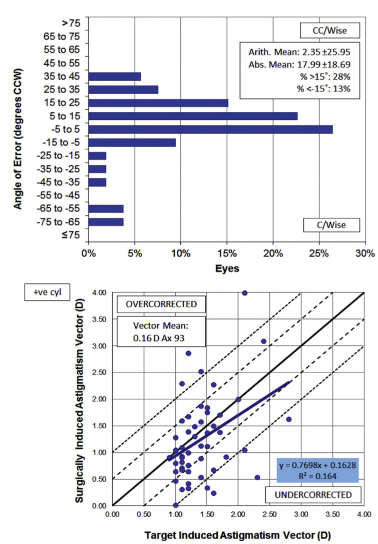

Figure 6. The astigmatism angles of error and the TIA versus SIA graphs of patients treated with femtosecond laser arcuate keratotomies (Abs. = absolute; Arith. = arithmetic; Ax = axis; CCW = counterclockwise; CC/Wise = counterclockwise; C/Wise = clockwise; SIA = surgically induced astigmatism; TIA = target induced astigmatism).

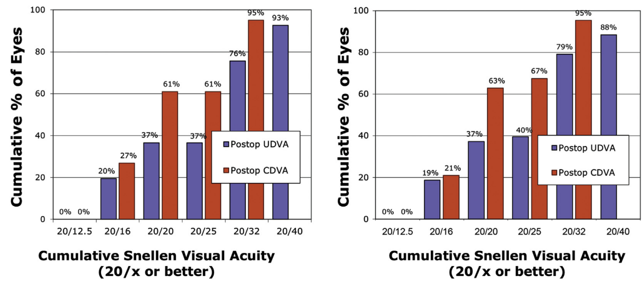

Figure 7. Cumulative percentages of postoperative Snellen visual acuity (UDVA and CDVA) of LRIs (*left*) and femtosecond laser arcuate keratotomies (*right*) (CDVA = corrected distance visual acuity; LRIs = limbal relaxing incisions; UDVA = uncorrected distance visual acuity).

Despite randomization, there were some statistically significant differences at baseline between the 2 groups; that is, worse visual acuity (by 12 letters) and a longer AL (by 0.7 mm) in the femtosecond group. However, there were no differences in the preoperative astigmatism or K values. We believe that the differences in acuity and AL did not play a significant role in the outcome parameters in this current study.

In summary, we found that both manual LRIs and femtosecond laser intrastromal arcuate keratotomies were safe

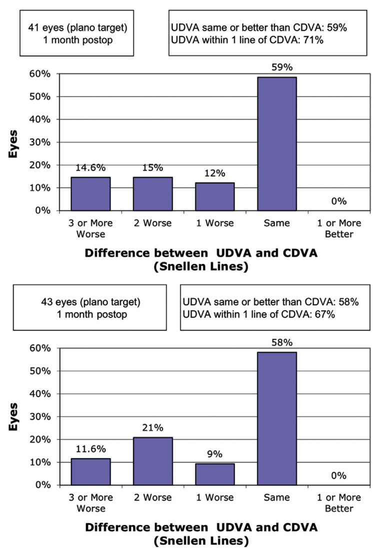

Figure 8. Number of lines difference between UDVA and CDVA of LRIs (*top*) and femtosecond laser arcuate keratotomies (*bottom*) (CDVA = corrected distance visual acuity; LRIs = limbal relaxing incisions; UDVA = uncorrected distance visual acuity).

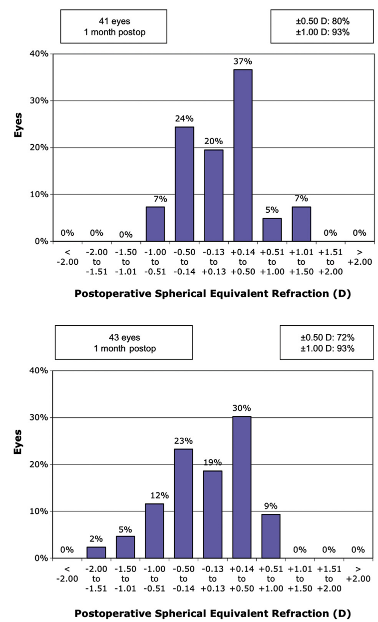

Figure 9. Spherical equivalent refractive accuracy of LRIs (*top*) and femtosecond laser arcuate keratotomies (*bottom*) (LRIs = limbal relaxing incisions).

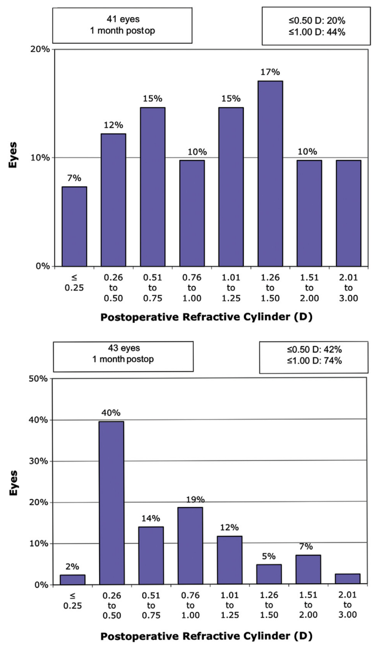

Figure 10. Preoperative and postoperative refractive astigmatism of LRIs (*top*) and femtosecond laser arcuate keratotomies (*bottom*) (LRIs = limbal relaxing incisions).

and easy to perform, with both achieving a meaningful reduction in corneal astigmatism. However, the laser group achieved a correction of greater magnitude than the LRI cohort 4 weeks after surgery.

WHAT WAS KNOWN

- Femtosecond laser intrastromal keratotomies and LRIs can both be used in the management of corneal cylinder at the time of cataract surgery

WHAT THIS PAPER ADDS

- Femtosecond laser arcuate keratotomies might offer more efficacious and accurate correction of corneal cylinder than LRIs.

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